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Characterization of noise and vibration exposure in Canadian Forces land vehicles

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Defence R&D Canada – Toronto
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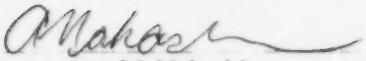

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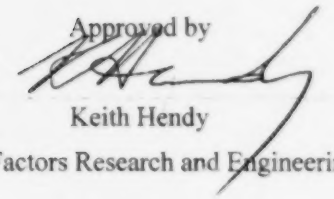

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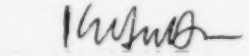

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Abstract

Measurements of whole-body vibration and noise were made in several Canadian Forces (CF) armoured vehicles to quantify and assess the exposure levels according to national and international standards. The measurements were made in the M113A2, Coyote, LAV III, Bison and M113A2 ADATS (air defence anti-tank system). In all vehicles except the ADATS, noise and vibration signals were recorded when the vehicles were idling, driven over rough terrain and driven on the highway. The ADATS was assessed while idling, driven at 8 km/h and driven at 32 km/h on a paved track. For each condition in each vehicle, the vibration and noise were recorded at the crewmember positions inside the vehicle for 5 to 10 minutes. The measurements were made at the driver, crew commander and passenger positions in the M113A2 and Bison, the driver, crew commander and operator positions in the Coyote, and the driver and operator positions in the ADATS. The crewmembers were also asked to complete a Reaction to Noise and Vibration questionnaire at the completion of each vehicle measurement session. The ADATS was the noisiest of the vehicles measured, while the LAV III was the least noisy. Although the noise levels in all of the vehicles while mobile exceeded the Canadian Labour code exposure limit of 87 dBA for 8 hours (MOL, 1991), it was found that in most cases the noise exposure could be reduced to safe levels with the proper use of an effective communications headset. The vibration exposure was more difficult to assess because of the conflicting caution zones, action levels and exposure limits set by the various standards. However, the results indicated that caution should be taken with respect to the duration of vibration exposure. The questionnaire responses indicated that half the crewmembers had difficulty communicating in the vehicle noise, but few were affected by vibration. The latter result may be due to the relatively short exposure duration (there was no indication of a negative response to the vibration exposure).

Résumé

Nous avons réalisé des mesures des vibrations globales du corps et du bruit dans plusieurs véhicules blindés des Forces canadiennes, afin de quantifier et d'évaluer le degré d'exposition du personnel relativement aux normes canadiennes et internationales. Les mesures ont été prises dans les véhicules M113A2, Coyote, LAV III, Bison et M113A2 ADATS (système de défense aérienne contre les chars). Dans tous les cas, sauf celui de l'ADATS, nous avons enregistré le bruit et les vibrations dans les véhicules avec le moteur au ralenti, pilotés sur un terrain accidenté et conduits sur une route. Nous avons évalué l'ADATS au ralenti et conduit à 8 et 32 km/h sur une piste pavée. Dans tous les véhicules et pour chaque condition, nous avons mesuré le bruit et les vibrations aux postes de l'équipage pendant cinq à dix minutes. Nous avons pris des mesures aux postes du conducteur, du chef d'équipage et des passagers du M133A2 et du Bison; aux postes du conducteur, du chef d'équipage et de l'opérateur du Coyote; et aux postes du conducteur et de l'opérateur de l'ADATS. Après avoir terminé les mesures sur chaque véhicule, nous avons demandé aux membres de l'équipage de remplir un questionnaire sur leur réaction au bruit et aux vibrations. D'après nos mesures, l'ADATS était le véhicule le plus bruyant et le LAV III le moins bruyant. Bien que l'intensité du bruit dans tous les véhicules en déplacement excédait la limite d'exposition sur huit heures de 87 dBA du *Code canadien du travail* (ministère du Travail, 1991), nous avons trouvé que, dans la plupart des cas, l'utilisation correcte d'un casque d'écoute adéquat réduisait l'exposition au bruit à un niveau sécuritaire. Il a été plus difficile d'évaluer l'exposition aux vibrations puisque les diverses normes présentent des directives divergentes sur les zones de prudence, les seuils d'intervention et les limites d'exposition. Toutefois, nos résultats indiquent qu'en matière d'exposition aux vibrations, la prudence est nécessaire. Les réponses au questionnaire ont indiqué que si, à cause du bruit dans le véhicule, la moitié de l'équipage éprouvait des difficultés de communication peu d'entre eux étaient affectés par les vibrations. Ce résultat pourrait s'expliquer par la brièveté de l'exposition (nous n'avons relevé aucune indication d'une réaction adverse à l'exposition aux vibrations).

Executive summary

The objective of this study was to quantify and assess the noise and whole-body vibration exposure experienced by CF personnel in armoured vehicles. Previous measurements of vehicle noise have shown that the levels sometimes may be in excess of 100 dBA. However, there is little information available on the noise levels of vehicles that are currently in service. Previous vibration measurement studies performed by Defence Research and Development Canada date back about 20 years, and were analyzed using a vibration standard that is no longer valid. There is a clear need for knowledge of noise and vibration levels in current CF vehicles and assessments of the exposures according to current standards. A secondary objective of the study was to expand the collection of noise recordings at DRDC Toronto to include the interior noise of armoured vehicles to enable the modelling of wider range of operational environments in the Noise Simulation Facility.

Vibration and noise measurements were made in the M113A2, Coyote, LAV III, Bison and M113A2 ADATS (air defence anti-tank system) at CFB Borden and Oerlikon Contraves Inc. in Saint-Jean-sur-Richelieu, QC. The measurements were made at the driver, crew commander and passenger positions of the M113A2 and LAV III, the driver, crew commander and operator positions in the Coyote, and the driver and operator positions in the ADATS. The noise and vibration signals were recorded onto digital audio tape (DAT) for 1/3 octave band spectral analysis. Baseline noise and vibration signals were recorded when the vehicles were idling. The M113A2, Coyote, LAV III and Bison, which were assessed at CFB Borden, were driven on rough terrain in the training area and on a highway. The ADATS was assessed on the property of Oerlikon Contraves Inc. on a paved track. Since only one type of terrain was available, two different driving speeds (8 km/h and 32 km/h) were used. For all of the conditions, the noise and vibration were recorded for 5 to 10 minutes. At the completion of the measurements for each vehicle, the crewmembers were asked to complete a Reaction to Noise and Vibration questionnaire.

The noise levels inside the vehicles for the most part exceeded the Canada Labour code exposure limit of 87 dBA for 8 hours (MOL, 1991). The LAV III was the least noisy, with levels of 97 dBA for the noisiest condition (highway driving) and the ADATS was the noisiest, with levels as high as 115 dBA (driver noise while driving at 32 km/h with the hatches closed). However, in most of the conditions measured, it is possible to reduce the exposure to safe levels with the proper use of a communications headset with hearing protective capability. Despite this, the questionnaire responses indicated that half of the crewmembers felt that the noise made it difficult to communicate inside the vehicle.

The vibration levels were calculated and assessed using three different standards: ISO 2631-1 (International Organization for Standardization), BS 6841 (British Standards Institute) and Directive 2002/44/EC (European Parliament and of the Council). The three standards provide conflicting guidelines for caution zones, action values and exposure limits for whole-body vibration exposure, making the measurement results difficult to interpret. Generally, it was found that the vibration exposure in the worst cases (rough terrain driving, or any mobile condition for the ADATS) was sufficient enough to raise concern regarding the health and

safety of CF personnel. Guidelines for limiting the duration of vibration exposure based on current standards have been presented in this report.

This study has provided new information on the operational environment in armoured vehicles. Information about the noise levels and spectra will help in the choice of effective hearing protection for a particular vehicle or crew position. The noise recordings will be used for research studies in the Noise Simulation Facility, which had previously been lacking in armoured vehicle recordings. Vibration levels and spectra have been produced for the first time for these vehicles, enabling the creation of guidelines for duration of vibration exposure and providing new information that will be useful in the design of future experiments.

Nakashima, A. M., Borland, M. J. and Abel, S. M. 2005. Characterization of vibration and noise exposure in Canadian Forces Land Vehicles. DRDC Toronto TR 2005-241. Defence R&D Canada – Toronto.

Sommaire

Cette étude avait comme objectif de quantifier et d'évaluer l'exposition du personnel des Forces canadiennes au bruit et aux vibrations globales du corps dans les véhicules blindés. Des mesures antérieures indiquent que l'intensité du bruit dans les véhicules peut dépasser 100 dBA. Toutefois, on possède peu de données sur l'intensité du bruit dans les véhicules présentement en service. Les mesures antérieures de la vibration effectuées par Recherche et développement pour la défense Canada remontent à environ vingt ans et ont été analysées relativement à des normes de vibration qui ne sont plus valides. Il existe des carences évidentes dans nos connaissances sur l'intensité du bruit et des vibrations dans les véhicules actuels des Forces, et de l'évaluation de l'exposition au bruit relativement aux normes actuelles. Cette étude avait comme objectif secondaire d'ajouter à la collection d'enregistrements de bruits de RDDC Toronto, les bruits dans les véhicules blindés, afin de modéliser une gamme plus vaste d'environnements d'opérations dans l'Installation de simulation de bruit.

Nous avons mesuré les vibrations et le bruit dans le M113A2, le Coyote, le LAV III, le Bison et le M113A2 ADATS (système de défense aérienne contre les chars) à la BFC Borden et chez Oerlikon Contraves Inc. à Saint-Jean-sur-Richelieu (Québec). Nous avons pris des mesures aux postes du conducteur, du chef d'équipage et des passagers du M113A2 et du LAV III; aux postes du conducteur, du chef d'équipage et de l'opérateur du Coyote; et aux postes du conducteur et de l'opérateur de l'ADATS. Les bruits et les vibrations ont été enregistrés sur une bande audionumérique (DAT) pour l'analyse spectrale sur une bande d'un tiers d'octave. Nous avons mesuré les signaux de référence pour le bruit et les vibrations dans chaque véhicule avec leur moteur au ralenti. Le M113A2, le Coyote, le LAV III et le Bison, évalués à la BFC Borden, ont été conduits sur le terrain accidenté de la zone d'entraînement et sur une route. L'ADATS a été évalué sur une piste pavée des terrains de Oerlikon Contraves Inc. Puisque nous ne disposions que d'un seul type de terrain, nous avons conduit le véhicule à deux vitesses différentes (8 et 32 km/h). Nous avons mesuré le bruit et les vibrations dans toutes ces conditions pendant cinq à dix minutes. Une fois les mesures terminées dans chaque véhicule, nous avons demandé aux membres de l'équipage de remplir un questionnaire sur leur réaction au bruit et aux vibrations.

Généralement, l'intensité du bruit à l'intérieur des véhicules excédait la limite d'exposition sur huit heures de 87 dBA du *Code canadien du travail* (ministère du Travail, 1991). Le LAV III était le véhicule le moins bruyant, présentant une intensité de 97 dBA pour les pires conditions (conduite sur route) et l'ADATS le plus bruyant, dans lequel on a enregistré une intensité sonore s'élevant à 115 dBA (bruit perçu par le conducteur, alors qu'il circulait à 32 km/h, avec les trappes fermées). Or, dans la plupart des conditions de l'expérience, on a pu réduire l'exposition au son à des niveaux acceptables en utilisant correctement un casque d'écoute muni de la protection adéquate de l'ouïe. Toutefois, les réponses au questionnaire indiquent que la moitié de l'équipage sentait que le bruit rendait plus difficile les communications à l'intérieur du véhicule.

Nous avons calculé l'intensité des vibrations relativement à trois normes : ISO 2631-1 (de l'Organisation internationale de normalisation), BS 6841 (de l'institut britannique de

normalisation) et la directive 2002/44/EC (du Parlement et du Conseil européens). L'interprétation des résultats des mesures est difficile puisque les trois normes présentent, pour les vibrations globales, des directives divergentes sur les zones de prudence, les seuils d'intervention et les limites d'exposition. Normalement, on trouve que, dans les pires cas (conduite sur terrain accidenté ou, dans le cas de l'ADATS, tout déplacement), l'exposition aux vibrations était suffisamment intense pour susciter des inquiétudes pour la santé et la sécurité du personnel des Forces. Dans ce rapport, nous présentons des directives visant à limiter la durée de l'exposition aux vibrations tirées des normes actuelles.

Cette étude contient de nouvelles informations sur l'environnement des opérations dans les véhicules blindés. Les informations présentées sur l'intensité et le spectre du bruit contribueront au choix de dispositifs efficaces de protection de l'ouïe, en fonction du véhicule ou du poste occupé par l'équipier. Les enregistrements du bruit dans les véhicules blindés seront utilisés lors de recherches dans l'Installation de simulation de bruit, laquelle ne possédait pas de telles données. Cette étude a permis de produire, pour la première fois dans le cas de ces véhicules, des intensités et des spectres des vibrations qui serviront à élaborer des directives sur la durée de l'exposition et qui seront utiles pour la conception de futures expériences.

Nakashima, A. M., Borland, M. J. and Abel, S. M. 2005. Characterization of vibration and noise exposure in Canadian Forces Land Vehicles. DRDC Toronto TR 2005-241 Defence R&D Canada – Toronto.

Table of contents

Abstract i

Résumé ii

Executive summary iii

Sommaire v

Table of contents vii

List of figures ix

List of tables xi

Acknowledgements xii

Background 1

Assessment of noise and whole-body vibration exposure 3

Methods and materials 7

- Subjects 7
- Apparatus 7
- Procedure 8

Results 13

- Noise levels: Borden measurements 13
- Noise levels: Oerlikon measurements 15
- Vibration levels 16
- Vibration dose values 20
- Questionnaire responses 22

Discussion 25

- Noise exposure 25
- Whole-body vibration exposure 28

Future work 31

Conclusions 32

References 33

List of Acronyms/Abbreviations 34

Appendix A: Armoured Vehicle Photos 35

Appendix B: Noise data 40

Appendix C: Whole-body vibration data 43

Appendix D: Questionnaire 55

List of figures

Figure 1. Placement of vibration accelerometers in the a. M113A2, b. Coyote, c. LAV III and d. Bison MRT (mobile repair team). 9

Figure 2. Placement of the vibration accelerometers in the M113A2 ADATS. 10

Figure A1. M113A2 front view 35

Figure A2. M113A2 cabin 36

Figure A3. Coyote navigator seat 36

Figure A4. LAV III 37

Figure A5. LAV III cabin 37

Figure A6. Bison MRT variant 38

Figure A7. Bison MRT variant cabin 38

Figure A8. M113 ADATS 39

Figure A9. M113 ADATS operator seats 39

Figure B1. LAV III driver noise 40

Figure B2. LAV III crew commander noise 40

Figure B3. Bison driver noise 41

Figure B4. Bison crew commander noise 41

Figure B5. M113 ADATS driver noise 42

Figure B6. M113 ADATS operator noise 42

Figure C1. LAV III driver x vibration 43

Figure C2. LAV III driver y vibration 43

Figure C3. LAV III driver z vibration 44

Figure C4. LAV III crew commander x vibration 44

Figure C5. LAV III crew commander y vibration 45

Figure C6. LAV III crew commander z vibration 45
Figure C7. LAV III passenger x vibration 46
Figure C8. LAV III passenger y vibration 46
Figure C9. LAV III passenger z vibration 47
Figure C10. Bison driver x vibration 47
Figure C11. Bison driver y vibration 48
Figure C12. Bison driver z vibration 48
Figure C13. Bison crew commander x vibration 49
Figure C14. Bison crew commander y vibration 49
Figure C15. Bison crew commander z vibration 50
Figure C16. Bison passenger x vibration 50
Figure C17. Bison passenger y vibration 51
Figure C18. Bison passenger z vibration 51
Figure C19. M113 ADATS driver x vibration 52
Figure C20. M113 ADATS driver y vibration 52
Figure C21. M113 ADATS driver z vibration 53
Figure C22. M113 ADATS operator x vibration 53
Figure C23. M113 ADATS operator y vibration 54
Figure C24. M113 ADATS operator z vibration 54

List of tables

Table 1. Frequency weightings from 1 to 80 Hz for the evaluation of whole-body vibration. .. 4

Table 2. Possible reactions to vibration magnitudes (BSI, 1987; ISO, 1997). 6

Table 3. Noise measurement conditions for the M113A2 ADATS..... 11

Table 4. Noise levels for vehicles measured at CFB Borden. 14

Table 5. Noise levels for M113A2 ADATS 16

Table 6. Correction values for the low frequency response of the DAT recorders. 17

Table 7. LAV III whole-body vibration data..... 18

Table 8. Bison whole-body vibration data..... 19

Table 9. M113A2 ADATS whole-body vibration data 20

Table 10. Time (hours) to reach exposure threshold or limit dose values..... 21

Table 11. Questionnaire responses indicating a negative reaction to noise and/or vibration.. 23

Table 12. Manufacturer specified attenuation for the Racal Slimgard II headset. 26

Table 13. Approximate noise exposure with and without the Racal Slimgard II headset. 27

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Background

Canadian Forces (CF) personnel are exposed to high levels of noise and vibration in armoured vehicles. Previous measurements in land vehicles have shown that the noise levels at the various crew positions were in excess of 100 dBA (e.g. Leopard C1 main battle tank [Forshaw and Crabtree, 1983]). Although noise levels have been measured and recorded in many CF vehicles in the past, few of these vehicles are still in service. Whole-body vibration in armoured vehicles was last studied by DRDC personnel 20 years ago. Maret and Winship (1972) made vibration measurements in five different armoured vehicles: M113 Armoured Personnel Carrier, M109 Howitzer, M113 ½ Lynx, Centurion Tank and M548 Cargo Carrier. Of these five vehicles, four are no longer in use or are being phased out, and the other vehicle (M113) is in the process of being upgraded. In addition, some of the data were lost due to equipment failures. The M113 and Centurion Tank were also studied by Forshaw and Ries (1986). The total vibration levels in the z-axis (buttocks-to-head for a seated person) were assessed according to a previous version of the International Standard for human exposure to whole-body vibration (ISO 2631:1978 Amendment 1-1982), which defined exposure limits, reduced comfort boundaries and fatigue-decreased proficiency boundaries. These limits are not included in the current International Standard (ISO 2631-1:1997) due to a lack of supporting experimental data.

To date it has not been possible to obtain reliable vibration data in CF armoured vehicles that would enable spectral analysis. An attempt at spectral analysis was made in the study of Maret and Winship (1972), but much of the data was lost due to electronic equipment failures. Spectral analysis of the vibration signal is essential for characterizing the vibration environment. In addition, there is no vibration data available for vehicles that have entered service in recent years.

The objective of the study was to characterize the vibration and noise levels at different positions inside several armoured vehicles. Comparison of the vibration and noise levels with existing standards will enable the development of guidelines for hearing protector selection and safe vibration exposure, thus making a significant impact on improving the health and safety of CF personnel. A second aim was the creation of noise recordings for use in the DRDC Toronto Noise Simulation Facility. The current collection of noise recordings is comprised mainly of aircraft noise and does not have any armoured vehicle crew noise. The addition of land vehicle noise recordings would greatly broaden the range of operational environments that can be modelled in the facility.

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Assessment of noise and whole-body vibration exposure

According to the Ministry of Labour, the noise exposure limit for an 8-hr workday is 87 dBA (MOL, 1991). Noise exposure standards use A-weighted sound levels. The unit dBA indicates that the sound pressure level has been subjected to a weighting network that de-emphasizes the low-frequency components of the sound to model subjective loudness (Tempest, 1985; Berglund and Lindvall, 1995). For exposure times of longer or shorter than 8 hours, the equal-energy rule applies. A doubling of energy is equal to an increase of 3 dBA. Thus, based on the 87 dBA limit for 8 hours, the exposure limit for 4 hours would be 90 dBA, and the limit for 16 hours would be 84 dBA.

Methods for measuring, evaluating and assessing whole-body vibration and repeated shock are given in the standards ISO 2631 (International Organization for Standardization [ISO, 1997]) and BS 6841 (British Standards Institute [BSI, 1987]). The basic equations given in the two standards for calculating the vibration levels are similar, although the methods of calculating the exposure differ slightly. The standards have been compared and contrasted extensively elsewhere (Griffin, 1998). The basic equations are presented in this section.

Human response to vibration is strongly frequency-dependent. The primary quantity of vibration magnitude is the root-mean-squared (RMS) acceleration, given by

$$a_{w\,RMS} = \left[\frac{1}{T} \int_0^T a_w^2(t) dt \right]^{\frac{1}{2}} \tag{1}$$

where $a_w(t)$ is the frequency-weighted acceleration as a function of time, t, in m/s^2 and T is the duration of measurement, in seconds. ISO 2631 and BS 6841 give different frequency weightings for the x-, y- and z-axes depending on how the vibration exposure is being evaluated. ISO 2631 specifies frequency weightings w_d for the x- and y-axes and w_k for the z-axis when evaluating the vibration of a seated person with regard to health. BS 6841 does not specify a weighting that should be used specifically for when health effects are of interest, but does specify frequency weightings w_d for the x- and y-axes and w_h for the z-axis when evaluating the discomfort of a seated person. The ISO and BS weightings are listed in Table 1. The weighted acceleration is calculated for each axis, and the total RMS acceleration is calculated as

$$a_{tot} = (k_x^2 a_{wxRMS}^2 + k_y^2 a_{wyRMS}^2 + k_z^2 a_{wzRMS}^2)^{\frac{1}{2}} \tag{2}$$

where a_{wxRMS}, a_{wyRMS} and a_{wzRMS} are the weighted RMS accelerations and k_x, k_y and k_z are the multiplying factors with respect to the x-, y- and z-axes, respectively. ISO 2631 recommends values of $k_x = 1.4$, $k_y = 1.4$ and $k_z = 1.0$ for assessment with respect to human health, while BS 6841 recommends that all three factors be unity.

Table 1. *Frequency weightings from 1 to 80 Hz for the evaluation of whole-body vibration.*

FREQUENCY (HZ)	ISO WEIGHTING (DB)		BS WEIGHTING (DB)	
	W_d (x- and y-axes)	W_k (z-axis)	W_d (x- and y-axes)	W_b (z-axis)
1	0.1	-6.33	0.10	-8.29
1.25	0.1	-6.29	0.07	-8.27
1.6	-0.28	-6.12	-0.28	-8.13
2.0	-1.01	-5.49	-1.01	-7.60
2.5	-2.20	-4.01	-2.20	-6.13
3.15	-3.85	-1.90	-3.85	-3.58
4.0	-5.82	-0.29	-5.81	-1.02
5.0	-7.76	0.33	-7.77	0.21
6.3	-9.81	0.46	-9.82	0.47
8.0	-11.9	0.31	-11.9	0.21
10.0	-13.9	-0.10	-13.9	-0.23
12.5	-15.9	-0.89	-15.9	-0.85
16	-18.0	-2.28	-18.1	-1.83
20	-20.0	-3.93	-20.0	-3.00
25	-21.9	-5.80	-21.9	-4.44
31.5	-24.0	-7.86	-24.0	-6.16
40	-26.1	-10.1	-26.2	-8.11
50	-28.2	-12.2	-28.2	-10.1
63	-30.6	-14.6	-30.5	-12.4
80	-33.5	-17.6	-33.6	-15.3

In addition to the RMS acceleration given by Equations 1 and 2, the vibration exposure can also be quantified by the vibration dose value (VDV), also called the fourth power vibration dose method (ISO, 1997). The VDV is calculated as

$$\mathrm{VDV} = \left\{ \int_0^T [a_w(t)]^4 \, dt \right\}^{\frac{1}{4}} \tag{3}$$

in units of $m/s^{1.75}$, where $a_w(t)$ is the instantaneous frequency-weighted acceleration as a function of the time, t, and T is the duration of measurement. Alternatively, the VDV can be estimated from the RMS acceleration by

$$\mathrm{eVDV} = 1.4 a_{wRMS} T^{\frac{1}{4}} \tag{4}$$

where a_{wRMS} is the RMS acceleration for the time period T. When using the eVDV, it is assumed that a_{wRMS} was calculated for a period when the vibration acceleration was relatively constant. If there is a total of N vibration periods in a day, the total vibration dose value can be calculated by

$$\mathrm{VDV}_{\mathrm{tot}} = \left(\sum_{n=1}^{n=N} \mathrm{VDV}_n^4 \right)^{\frac{1}{4}} \tag{5}$$

ISO 2631 and BS 6841 do not explicitly state vibration exposure limits. The standards provide identical guidelines for possible reactions to vibration magnitudes; this is shown in Table 2. ISO 2631 gives a health guidance caution zone based on the weighted acceleration and exposure time, whose lower and upper limits are approximately equal to VDV of 8.5 $m/s^{1.75}$ and 17 $m/s^{1.75}$, respectively (ISO, 1997). BS 6841 suggests that VDV in the regions of 15 $m/s^{1.75}$ will cause severe discomfort, and acceleration values in any axis should not exceed 0.5 m/s^2 when tasks involving fine motor control or visual acuity are being performed (BSI, 1987). The 15 $m/s^{1.75}$ guideline is also referred to as the action value. There is also Directive 2002/44/EC of the European Parliament and of the Council, which gives the minimum requirements for the protection of workers from risks to their health and safety arising from vibration exposure (Directive 2002/04/EC, 2002 [hereafter referred to as the EU standard]). This standard gives a daily exposure action value standardized to an 8-hr reference period of 0.5 m/s^2 or 21 $m/s^{1.75}$, and a daily exposure limit of 1.15 m/s^2 or 21 $m/s^{1.75}$. When the vibration exposure in the workplace exceeds the action value, employers are obligated to implement programs to minimize the exposure. All three standards were used in the analysis of results for this study.

Table 2. *Possible reactions to vibration magnitudes (BSI, 1987; ISO, 1997).*

< 0.315 m/s^2	Not uncomfortable
0.315 to 0.63 m/s^2	A little uncomfortable
0.5 to 1.0 m/s^2	Fairly uncomfortable
0.8 to 1.6 m/s^2	Uncomfortable
1.25 to 2.5 m/s^2	Very uncomfortable
> 2.0 m/s^2	Extremely uncomfortable

Methods and materials

Subjects

Ten male subjects (9 military and 1 civilian who was an armoured vehicle mechanic), ranging in age from 19 to 46 years (median: 35 years), weight from 66 to 90 kg (median: 77 kg) and height from 170 to 183 cm (median: 174 cm) participated. Because of a lack of available personnel, two of the military subjects participated in the study twice. In addition, one of the subjects was French-speaking and unable to complete the questionnaire, which was in English only. In total, 12 sets of noise and vibration data and 9 sets of questionnaire responses were obtained.

Apparatus

Vehicles

Five types of vehicles were used in the study: Coyote, Bison MRT variant (mobile repair team), LAV III (light-armoured vehicle), M113A2 and M113A2 ADATS (anti-tank air defense system). The Coyote, Bison and LAV III are wheeled vehicles, while the M113A2 is tracked. Photographs of all of the vehicles are shown in Appendix A.

Noise measurements

The noise measurements were made with a 1/4" microphone (Bruel and Kjaer, Model 4135) or a sound level meter (Quest Technologies, Model 1900). The microphones were attached to the headgear of the subjects. The ambient noise was recorded with DAT recorders (Sony, Model PCM-M1).

Whole-body vibration measurements

Whole-body vibration of a seated person was measured using a seat pad containing 3 accelerometers (vibration sensors). The accelerometers measured the vibration in the x- (fore-to-aft), y- (left-to-right side) and z- (buttocks-to-head) axes. The subject sat on the seat pad that was aligned on the seat, such that the transmission of the vibration from the vehicle to the body was measured in 3 axes. Since the crew commander typically spends considerably more time in the vehicle standing on the seat than sitting, a triaxial accelerometer was mounted on the frame of the seat. In this case, the z-axis was the line between the feet and the head. The seat pad or triaxial accelerometer was connected to a HAVPro human vibration meter (Quest Technologies), which logged the total vibration levels in each axis in units of meters per second squared (m/s^2). The output for each of three axes were also recorded with DAT recorders (Sony PCM-M1) to enable analysis of the vibration spectra.

Procedure

Measurements at CFB Borden

Noise and whole-body vibration measurements of the M113A2, Coyote, LAV III and Bison were made on 11 and 15 April 2005. On the first day of measurements, the M113A2 and the Coyote were assessed. The weather was sunny and the paved roads and dirt field in the training area were dry. The temperature ranged from –5.5 to 12.2°C. On the second day, the LAV III and Bison were measured. The weather was sunny with the temperature ranging from –8 to 15.8°C. Both the paved roads and training area were dry.

For the M113A2, LAV III and Bison, seat pad accelerometers were placed on the driver seat and passenger bench. The passenger was seated facing sideways in the vehicle. For the Coyote, seat pad accelerometers were placed on the driver seat and navigator seat. The crew commander vibration was measured with a triaxial accelerometer that was mounted on the frame of the seat. Schematic diagrams of the interior of each vehicle are shown in Figures 1 and 2, and photographs are shown in Appendix A. Microphones were taped to the right side of the subjects' helmets (driver, crew commander and passenger) to capture the ambient noise near ear level. The subjects were instructed to wear their normal headgear for the experiment, i.e. they were not forced to wear additional hearing protection. It was observed that the drivers and crew commanders wore communication headsets with their helmets, while the passengers wore only a helmet.

Microphone and accelerometer calibration signals were recorded onto DAT. Noise and vibration signals were recorded for three different conditions: idling (5 min), rough terrain (10 min) and high-speed highway driving (10 min). Two sets of measurements were made for each condition so that both the raw (unweighted) and weighted vibration signal from the HAVPro could be recorded. For the rough terrain runs, the vehicle speed was variable depending on the difficulty of the terrain. For the highway runs, the M113A2 was driven at about 70 km/h (45 mph), and the Coyote, LAV III and Bison were driven at about 80 km/h. After the measurements were made in each vehicle, the subjects completed a Reaction to Noise and Vibration Questionnaire (Appendix D).

Due to equipment problems on the first day of measurements, most of the noise and vibration data for the M113A2 and the Coyote was lost; only the overall noise levels for the passenger were recorded.

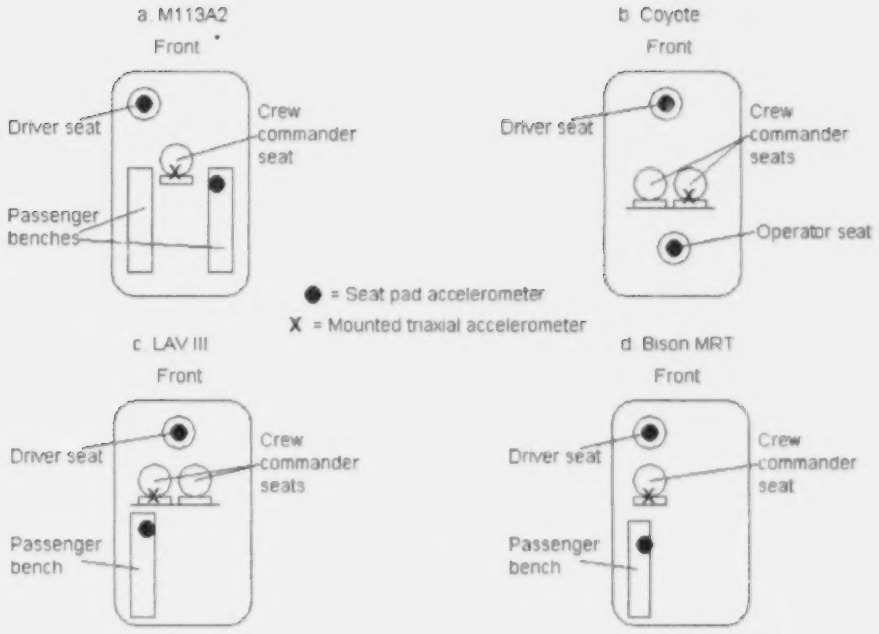

Figure 1. Placement of vibration accelerometers in the a. M113A2, b. Coyote, c. LAV III and d. Bison MRT (mobile repair team).

Measurements at Oerlikon Contraves Inc.

Noise and vibration measurements of the M113A2 ADATS were made at Oerlikon Contraves Inc. on 5 and 6 July 2005. The ADATS is a mobile low-level air defence unit that was designed to provide air defence protection for mobile troops and ground installations. A number of different systems contribute to the overall noise levels, including the primary power unit (PPU), hydraulic power system (HPS), radar console and electrical cabinet, and a vehicle ventilation system (either an air conditioning unit [ACU] or micro climate unit [MCU]). The noise measurements were made at the request of the Directorate of Armoured Vehicle Program Management (DAVPM); thus, the measurement procedure was different from that followed at CFB Borden due to the client's requirements. The noise was recorded in 2 different vehicles: one was equipped with an ACU and the other was equipped with an MCU. The conditions on the first day of measurements were overcast with light rain, with the temperature ranging from 25 to 31°C. Whole-body vibration measurements were made on the second day; the conditions were sunny and the temperature range was 13 to 23°C.

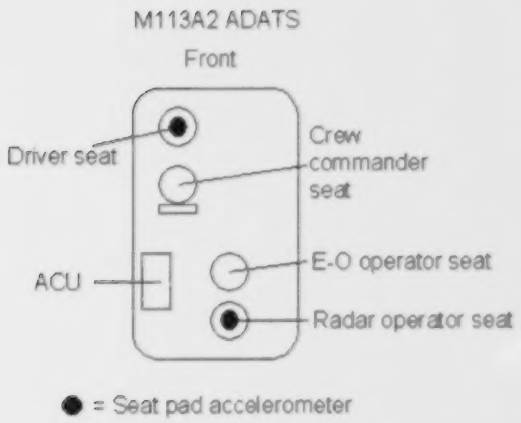

Figure 2. Placement of the vibration accelerometers in the M113A2 ADATS.

Noise measurements were made at the driver and two operator seats (E-O [electro-optical] and radar operator; see Figure 2 for schematic diagram). All three wore communication headsets, and the microphones were taped to the right side of the headsets to capture the noise near ear level. Whole-body vibration measurements were made at the driver and the radar operator seats using seat-pad accelerometers. The crew commander seat was not used in this vehicle.

Microphone calibration signals were recorded onto DAT. Noise measurements were made for three different conditions: idling, driving at 5 mph (8 km/h) and driving at 20 mph (32 km/h). The idling measurements were made with the driver and crew commander hatches closed, while the mobile measurements were made with both hatches closed, both hatches open, and crew commander hatch open, driver hatch closed. The test conditions are listed in Table 3. For each of the test conditions, the noise was recorded for 5 min.

Whole-body vibration measurements for one vehicle only (ADATS with ACU) were made at the driver and radar operator seats (see Figure 2). Accelerometer calibration signals were recorded onto DAT, and the vibration was measured for three different conditions: idling, driving at 8 km/h and driving at 32 km/h. Vibration signals were recorded for 5 min for each condition. Two sets of measurements were made for each condition so that both the raw (unweighted) and weighted vibration signal from the HAVPro could be recorded. After the vibration measurements were finished, the driver and operator completed the Reaction to Noise and Vibration Questionnaire (Appendix D).

Table 3. Noise measurement conditions for the M113A2 ADATS.

SYSTEMS ON	HATCH CONFIGURATION	VEHICLE SPEED (KM/H)
All except ACU/MCU	Both closed	0
All on	Both closed	0
All on	Both closed	8
All on	Both closed	32
All on except HPS	Both open	8
All on except HPS	Both open	32
All on except HPS	Crew commander open	8
All on except HPS	Crew commander open	32

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Results

Noise levels: Borden measurements

Overall noise levels for the vehicles measured at CFB Borden (LAV III, Bison, Coyote and M113A2) are shown in Table 4. The noise for the driver and crew commander was recorded onto DAT, also enabling the calculation of the overall A-weighted levels (shown in Table 4) and 1/3 octave band spectra (shown in Appendix B, Figures B1 to B4 for the LAV III and Bison). The total A-weighted sound pressure level is indicated on the 1/3 octave band spectra graphs as "A" and the total unweighted level is indicated as "L." Due to the limited number of DAT recorders, only the overall noise levels for the passenger were logged with the sound level meter (shown in Table 4). Equipment problems on the first day of measurements corrupted the recordings, and thus the noise data for the driver and crew commander of the M113A2 and Coyote were lost.

LAV III driver noise

The 1/3 octave band noise spectra for the driver of the LAV III are shown in Figure B1. The idling noise spectrum showed peaks in the 20, 31.5, 40 and 63 Hz bands. The total A-weighted level (84.2 dBA) was thus substantially lower than the unweighted level (98.6 dB). The noise spectra for rough terrain and highway driving did not show any distinct peaks. The difference between the A-weighted and unweighted levels was almost the same for all conditions (90.9 dBA and 103.3 dB for rough terrain and 96.6 dBA and 110 dB for highway), indicating that an increase in vehicle speed increased the noise levels at all frequencies.

LAV III crew commander noise

The noise spectra for the crew commander (standing) of the LAV III are shown in Figure B2. The spectra for all conditions were similar in shape to those for the driver (Figure B1), although the idling noise levels were lower (A-weighted 73.3 dBA and unweighted 92.2 dB for the crew commander compared to 84.2 dBA and 98.6 dB for the driver).

Bison driver noise

Figure B3 shows the noise spectra for the Bison driver. The idling spectrum showed peaks in the 31.5 and 100 Hz bands, causing the unweighted level to be almost 20 dB higher than the A-weighted level (92.2 dB compared to 73.3 dBA). The spectra for rough terrain and highway driving were almost identical at frequencies above 200 Hz. Below 200 Hz, the highway driving noise was about 10 dB higher than for rough terrain in most of the bands. Since the increase was only at lower frequencies, the total A-weighted levels for rough terrain and highway driving were the same (102 dBA).

***Table 4**. Noise levels for vehicles measured at CFB Borden*

VEHICLE	POSITION	CONDITION	TOTAL SPL UNWEIGHTED (DB)	TOTAL SPL A-WEIGHTED (DBA)
LAV III	Driver	Idle	98.6	84.2
		Rough terrain	103	90.9
		Highway	110	96.6
	Crew Commander	Idle	92.2	73.3
		Rough Terrain	104	91.2
		Highway	110	96.6
	Passenger	Idle	103	--
		Rough Terrain	106	--
		Highway	113	--
Bison	Driver	Idle	94.6	89.4
		Rough Terrain	107	102
		Highway	114	102
	Crew Commander	Idle	96.9	88.5
		Rough Terrain	108	102
		Highway	117	102
	Passenger	Idle	94.6	--
		Rough Terrain	104	--
		Highway	110	--
M113A2	Passenger	Idle	--	--
		Rough Terrain	112	--
		Highway	116	--
Coyote	Operator	Idle	--	--
		Rough Terrain	106	--
		Highway	114	--

-- no data available

Bison crew commander noise

The noise spectra for the Bison crew commander, shown in Figure B4, are similar in shape to those for the driver, as are the total noise levels for all three conditions.

Cabin noise

The total unweighted levels inside the cabin for the LAV III, Bison, M113A2 and Coyote were logged with a sound level meter (see Table 4). For the LAV III, Bison and M113A2, the noise levels are for a passenger sitting on the bench with the hatch open. For the Coyote, the noise levels are for the operator. The highway driving condition was the most intense for all vehicles, with levels ranging from 110 to 117 dB. For the LAV III, the noise levels in the cabin were higher than that for the crew commander and driver, while the opposite was true for the Bison. However, since the A-weighted levels were not measured, the actual noise exposures cannot be compared.

Noise levels: Oerlikon measurements

The overall noise levels for the ADATS are shown in Table 5, and the spectra are shown in Appendix B, Figures B5 and B6. Only the data for the ADATS ACU are presented here since this was the vehicle that was also used for the vibration measurements. It was generally found that the overall noise levels and spectra for the ACU and MCU were similar. In addition, the noise levels at the two operator seats were found to be similar, so these results were averaged. Noise measurements were made while the driver and crew commander hatches were both open, both closed and crew commander hatch open, driver hatch closed. The noise levels and spectra for the one hatch closed condition were similar to the both hatches closed condition and are thus not shown.

ADATS driver noise

The noise spectra for the ADATS driver are shown in Figure B5. The noise levels and spectrum for the idling condition were similar to the 8 km/h driving condition (about 95 dBA [100 dB unweighted]). When the vehicle was driven at 32 km/h, the noise levels increased at all frequencies. With the hatches closed, the overall noise levels were 12 dB higher than when the hatches were open (unweighted 123 dB, A-weighted 115 dBA for hatches closed compared to 111dB, 103 dBA for hatches open).

ADATS operator noise

Figure B6 shows the noise spectra for the ADATS operator. When the vehicle was idling, there was little low-frequency noise with the exception of a peak at 125 Hz. There was also a peak at 400 Hz. Going from idling to a speed of 8 km/h caused a large increase in low frequency noise, increasing the overall unweighted noise levels from 101 dB (idling) to 110 dB (8 km/h). Increasing the speed to 32 km/h caused an

increase in noise at frequencies above 50 Hz. There was almost no difference between the noise levels or spectra when the hatches were open and closed.

Table 5. *Noise levels for M113A2 ADATS*

POSITION	CONDITION	TOTAL SPL UNWEIGHTED (DB)	TOTAL SPL A-WEIGHTED (DBA)
Driver	Idle	99.4	94.7
	Paved road, 8 km/h, hatches closed	113	103
	Paved road, 8 km/h, hatches open	100	94.5
	Paved road, 32 km/h, hatches closed	123	115
	Paved road, 32 km/h, hatches open	111	103
Operator	Idle	101	96.7
	Paved road, 8 km/h, hatches closed	109	99.7
	Paved road, 8 km/h, hatches open	110	100
	Paved road, 32 km/h, hatches closed	120	111
	Paved road, 32 km/h, hatches open	120	114

Vibration levels

The Sony PCM-M1 DAT recorders are not specialized for vibration recordings. The analysis of the vibration data was limited by the high sampling frequency (44.1 kHz) and the low frequency response of the recorder. The low frequency response of the DAT recorder was tested by recording pure tones in 1/3 octave bands from 1 to 10 Hz and comparing the recorded amplitude to that of a 100 Hz recorded signal. The relative levels were used to calculate correction values in dB, which were added to the corresponding 1/3 octave band levels of the vibration data. The correction values are shown in Table 6.

RMS acceleration values were calculated, with integration times T between 4 and 5 minutes (see Equation 1), depending on the amount of data that was available. The results for the driver, crew commander and passenger of the LAV III and Bison are listed in Tables 7 and 8. The values for the ADATS driver and operator are listed in Table 9. The RMS acceleration in the x, y, and z axes have been weighted according to ISO 2631 (ISO) and BS 6841 (BSI), and summed according to Equation 2. As recommended in ISO 2631-1, the ISO totals for the driver and passenger were calculated using $k = 1.4$ for the x- and y-axes and $k = 1.0$ for the z-

axes. For the crew commander, k = 1.0 was used for all axes. The BSI totals were calculated using k = 1.0 for all axes. The ISO frequency-weighted vibration spectra in 1/3 octave bands from 1 to 80 Hz are shown in Appendix C.

Table 6. *Correction values for the low frequency response of the DAT recorders.*

FREQUENCY (HZ)	CORRECTION VALUE (DB)
1	9.4
1.25	6.8
1.6	4.6
2	3.2
2.5	2.1
3.15	1.4
4	0.9
5	0.6
6.3	0.4
8	0.2
10	0.2

LAV III vibration levels

Table 7 shows the RMS acceleration values for the driver, crew commander and passenger of the LAV III. The z-axis was the dominant axis of vibration for all conditions at all 3 measurement positions. The vibration was worst while driving over rough terrain for all 3 positions, with total RMS acceleration values ranging from 0.53 to 0.74 m/s^2 (ISO) or 0.50 to 0.64 m/s^2 (BSI).

The vibration spectra are shown in Figures C1 through C9. When the vehicle was driven over rough terrain, the vibration in the x- and y-axes was generally highest around 1 Hz (Figures C1, C2, C4, C5, C7, C8), while for the z-axis, the vibration was highest around 4 to 5 Hz (Figures C3, C6, C9). During highway driving, the vibration in the z-axis was highest around 2.5 Hz (Figures C3, C6, C9); for the passenger, there was also a large peak in the 63 Hz band. The driver and crew commander x-axis vibration showed a peak in the 6.3 Hz band (Figures C1 and C4) while the passenger x-axis vibration was highest below 4 Hz, and from 50 to 63 Hz (Figure C7). For the

y-axis, the vibration was strongest in the lower frequencies (1 to 2 Hz) for the driver and crew commander (Figures C2 and C5), while the passenger y-axis vibration had a peak at 6.3 Hz (Figure C8).

Table 7. *LAV III whole-body vibration data*

POSITION	CONDITION	RMS ACCELERATION (M/S^2)							
		X		*Y*		*Z*		*Total*	
		ISO	*BSI*	*ISO*	*BSI*	*ISO*	*BSI*	*ISO*	*BSI*
Driver	Idle	0.03	0.03	0.03	0.03	0.09	0.10	0.11	0.11
	Rough terrain	0.17	0.17	0.20	0.20	0.66	0.59	0.71	0.64
	Highway	0.06	0.06	0.09	0.09	0.26	0.24	0.28	0.26
Crew Commander	Idle	0.04	0.04	0.03	0.03	0.12	0.14	0.13	0.15
	Rough terrain	0.14	0.14	0.16	0.16	0.49	0.45	0.53	0.50
	Highway	0.07	0.07	0.07	0.07	0.38	0.40	0.40	0.41
Passenger	Idle	0.02	0.02	0.01	0.01	0.07	0.09	0.07	0.09
	Rough terrain	0.21	0.21	0.16	0.16	0.64	0.56	0.74	0.62
	Highway	0.13	0.12	0.04	0.04	0.56	0.61	0.59	0.62

Bison vibration levels

The RMS acceleration values for the Bison are shown in Table 8. The idling and rough terrain vibration recordings for the crew commander were of poor quality and the vibration levels could not be calculated. The z-axis was the dominant axis of vibration except for passenger during rough terrain driving, in which case the vibration was highest in the y-axis. The highest total vibration levels were for the driver and passenger while driving over rough terrain (1.36 and 1.54 m/s^2, respectively [ISO], and 1.08 and 1.17 m/s^2, respectively [BSI]).

The vibration spectra are shown in Figures C10 through C18. The vibration was the greatest in the 1 Hz band when the vehicle was driven over rough terrain for all axes and positions. The vibration during highway driving was considerably lower than the rough terrain vibration at frequencies below about 25 Hz.

Table 8. Bison whole-body vibration data

POSITION	CONDITION	RMS ACCELERATION (M/S^2)							
		X		*Y*		*Z*		*Total*	
		ISO	*BSI*	*ISO*	*BSI*	*ISO*	*BSI*	*ISO*	*BSI*
Driver	Idle	0.07	0.07	0.04	0.04	0.15	0.13	0.19	0.16
	Rough terrain	0.45	0.45	0.37	0.37	1.10	0.91	1.36	1.08
	Highway	0.05	0.05	0.06	0.06	0.28	0.26	0.30	0.27
Crew Commander	Idle	0.04	0.04	--	--	--	--	--	--
	Rough terrain	0.33	0.33	--	--	--	--	--	--
	Highway	0.06	0.06	0.08	0.08	0.38	0.45	0.40	0.46
Passenger	Idle	0.01	0.01	0.01	0.01	0.03	0.03	0.03	0.03
	Rough terrain	0.33	0.33	1.75	1.75	1.08	0.93	1.54	1.17
	Highway	0.08	0.08	0.15	0.15	0.17	0.17	0.29	0.24

ADATS vibration levels

The RMS acceleration values for the ADATS are shown in Table 9. For this vehicle, the vibration levels for different driving speeds rather than different terrain are shown. The z-axis was the dominant axis of vibration for all conditions. The highest levels of vibration were experienced when the vehicle was driven at a higher speed (1.26 [ISO] and 1.22 m/s^2 [BSI] for the driver and 1.01 m/s^2 [same for ISO and BSI] for the operator).

The vibration spectra are shown in Figures C19 through C24. During 8 km/h driving, there was a peak in the 16 Hz band in the x-axis vibration (Figures C19 and C22) for both the driver and operator. The operator spectrum also showed peaks at 31.5 and 63 Hz. No distinct features were seen in the y-axis driver vibration spectrum at the slower driving speed; peaks around 2 Hz were seen at the higher speed (Figure C20). The operator y-axis spectrum showed peaks at 16 and 63 Hz (Figure C23). The z-axis vibration spectra showed more energy in the higher frequency bands than the lower. In some bands, the vibration levels were higher when the driving speed was 8 km/h than at 32 km/h (Figures C21 and C24). There were large peaks in the 80 Hz band for the driver x- and z-axes, and operator x- and z-axes at this driving speed.

Table 9. M113A2 ADATS whole-body vibration data

POSITION	CONDITION	RMS ACCELERATION (M/S^2)							
		X		*Y*		*Z*		*Total*	
		ISO	*BSI*	*ISO*	*BSI*	*ISO*	*BSI*	*ISO*	*BSI*
Driver	Idle	0.02	0.02	0.01	0.01	0.03	0.03	0.04	0.04
	Paved road, 8 km/h	0.12	0.12	0.13	0.13	0.57	0.66	0.62	0.68
	Paved road, 32 km/h	0.29	0.29	0.57	0.57	0.89	1.04	1.26	1.22
Operator	Idle	0.01	0.01	0.02	0.02	0.02	0.03	0.04	0.03
	Paved road, 8 km/h	0.14	0.14	0.15	0.15	0.83	0.93	0.87	0.95
	Paved road, 32 km/h	0.35	0.35	0.27	0.27	0.80	0.91	1.01	1.01

Vibration dose values

The vibration dose value (VDV) for a vibration signal measured over a time period T is calculated by Equation 3. Some of the vibration recordings, particularly for the Bison, contained sections of overloading that corrupted the signal. This made it difficult to calculate the VDV from Equation 3, which, according to BS 6841, should be determined from a vibration measurement obtained throughout a full exposure to vibration (BSI, 1987). To simplify the calculations, the estimated VDV (eVDV, Equation 4) was calculated for 30 sec sections of each recording and summed according to Equation 5. Since the vibration recordings for each vehicle, position and condition were not of exactly the same duration, the results are presented here as the exposure times required to reach certain dose values as defined by the ISO, BSI and EU standards, assuming that the vibration is constant throughout the period of exposure. For ISO 2631, the critical VDV are 8.5 $m/s^{1.75}$ and 17 $m/s^{1.75}$, which correspond to the lower and upper boundaries of the health guidance caution zone (ISO, 1997). BS 6841 states that a VDV of 15 $m/s^{1.75}$ will usually cause severe discomfort (BSI, 1987). The EU standard defines VDV of 9.1 $m/s^{1.75}$ as the "action value" (at which employers shall implement programs to minimize vibration exposure) and 21 $m/s^{1.75}$ as the daily exposure limit. The exposure times required to reach these VDV are listed in Table 10.

The conditions that posed the greatest risk to the crew were the Bison while driving on rough terrain and the ADATS while driving at 32 km/h. For the Bison, the driver and passenger would be at risk for injury within an 8-hr time period, according to both ISO 2631 and BS 6841. However, the exposures would not exceed the EU daily limit within 8 hours. The operator of the ADATS would also be at risk according to BS 6841 when the vehicle was driven at 8 km/h.

Table 10. *Time (hours) to reach exposure threshold or limit dose values.*

VEHICLE/ POSITION	CONDITION	TIME TO REACH THRESHOLD (HOURS)				
		ISO LOWER (8.5 $M/S^{1.75}$)	ISO UPPER (17 $M/S^{1.75}$)	BS (15 $M/S^{1.75}$)	EU ACTION VALUE (9.1 $M/S^{1.75}$)	EU DAILY LIMIT (21 $M/S^{1.75}$)
Bison driver	Rough terrain	0.3	4.9	6.2	0.4	12
	Highway	> 24	>> 24	>> 24	> 24	>> 24
Bison crew commander	Rough terrain	--	--	--	--	--
	Highway	19	>> 24	>> 24	> 24	>> 24
Bison passenger	Rough terrain	0.5	7.8	8.0	0.6	18
	Highway	>> 24	>> 24	>> 24	>> 24	>> 24
LAV III driver	Rough terrain	0.8	13	12	1.1	> 24
	Highway	> 24	>> 24	>> 24	> 24	>> 24
LAV III crew commander	Rough terrain	3.2	> 24	> 24	4.2	>> 24
	Highway	15	>> 24	>> 24	19	>> 24
LAV III passenger	Rough terrain	1.8	> 24	> 24	2.4	> 24
	Highway	3.8	> 24	> 24	5.1	>> 24
M113 ADATS driver	Paved road, 8 km/h	3.3	> 24	18	4.3	>> 24
	Paved road, 32 km/h	0.5	7.4	2.6	0.6	17
M113 ADATS operator	Paved road, 8 km/h	0.9	11	4.2	0.9	> 24
	Paved road, 32 km/h	1.1	13	5.0	1.1	> 24

-- indicates that no data was available

>24 indicates the number of hours is between 24.1 and 100

>> 24 indicates that the number of hours is greater than 100

Questionnaire responses

The Reaction to Noise and Vibration questionnaire is given in Appendix D. The subjects who participated in the ADATS measurement study answered a modified version of the questionnaire to reflect the driving conditions, which were different from the Borden measurements. A response of 1 corresponded to "Not at all" and a response a 5 corresponding to "very much," with 3 being neutral. The percentage of responses of 4 or 5, indicating a negative response to noise and/or vibration, were calculated for each question. The results are shown in Table 11.

About half of the respondents gave responses of 4 or 5 to questions 17 and 18, indicating that they had difficulty communicating in the noise. One-third of the respondents also indicated that the noise made them uncomfortable while the vehicle was driven at a high speed (question 15). Most of the questions asking about common reactions to vibration exposure (dizziness, fatigue, nausea, pain) were responded to as a 1 or a 2. One respondent commented that pain was experienced in the feet and back.

Table 11. *Questionnaire responses indicating a negative reaction to noise and/or vibration*

QUESTION	% RESPONSES OF 4 OR 5
13. When inside the vehicle (on-road/high speed), the vibration made me uncomfortable.	22
14. When inside the vehicle (off-road/slow speed), the vibration made me uncomfortable.	0
15. When inside the vehicle (on-road/high speed), the noise made me uncomfortable.	33
16. When inside the vehicle (off-road/slow speed), the noise made me uncomfortable.	22
17. When inside the vehicle (on-road/high speed), the noise made it difficult to communicate.	44
18. When inside the vehicle (off-road/slow speed), the noise made it difficult to communicate.	55
19. When inside the vehicle (on-road/high speed), I experienced circling of myself and /or surroundings.	0
20. When inside the vehicle (off-road/slow speed), I experienced circling of myself and/or surroundings.	0
21. When inside the vehicle (on-road/high speed), I felt nauseous.	0
22. When inside the vehicle (off-road/slow speed), I felt nauseous.	0
23. When inside the vehicle (on-road/high speed), I felt pain.	22
24. When inside the vehicle (off-road/slow speed), I felt pain.	11
25. After leaving the vehicle, I experienced circling of myself and/or surroundings.	0
26. After leaving the vehicle, it was difficult to find my footing.	0
27. After leaving the vehicle, I felt nauseous.	0
28. After leaving the vehicle, I felt fatigued.	22
29. After leaving the vehicle, I felt pain.	0

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Discussion

Noise exposure

With the exception of the LAV III during idling, all of the conditions, positions and vehicles studied had overall noise levels that exceeded the Canada Labour Code 8-hr noise exposure limit of 87 dBA (MOL, 1991). The LAV III was the least noisy of the vehicles for which complete noise data was obtained, followed by the Bison and then the ADATS. The data do not suggest any significant differences in noise exposure between the crewmembers in a given vehicle. The ADATS noise data, which were obtained with the hatches open and hatches closed, showed that the noise exposure for the driver could be more than 10 dB greater when the hatches were closed. It is thus recommended that the hatches be kept open whenever possible during driving.

In general, given the high noise levels, hearing protection should be worn at all times inside all of the vehicles, even when they are idling. The noise spectra for all of the vehicles were predominately low frequency, suggesting that headsets with ANR may be required to reduce the noise exposure to safe levels. When the noise levels exceed 105 dBA, as was the case for the ADATS under some driving conditions (see Table 5), it is recommended by Canadian Standards Association that double hearing protection be worn (CSA, 2002). However, the choice of the devices must be made with care such that radio communications are not affected. For example, an ANR earmuff in combination with an earplug may not be a good choice because although the ear would be well-protected from the vehicle noise, the increased attenuation given by the plug may cause the radio operator to increase the volume of the radio and speak louder, which in turn would increase the noise exposure at the ear.

The Racal Slimgard II communications headset, which is used in the ADATS, was tested at DRDC Toronto and found to produce noise attenuation similar to the manufacturer's specifications (see Table 12). The noise attenuation in octave bands from 125 to 4000 Hz were used to calculate the approximate noise exposure inside the vehicles when the headset is worn in passive (ANR off) and ANR modes. The 63 Hz band attenuation given by the manufacturer was not included in the calculations because the attenuation at this frequency could not be verified using the DRDC test facility. The approximate noise exposures with the headset are listed in Table 13. When worn in the passive mode, the headset provides sufficient attenuation for the LAV III and Bison for the noise exposure to fall within the 87 dBA 8-hr limit. For the ADATS, the headset must be worn in the ANR mode when the vehicle is driven at 32 km/h. In the case of the driver when the hatches are closed, the noise exposure would still be 88 dBA, and thus the exposure time should be no more than 4 hours. This is assuming that the headset is properly fitted and worn at all times. It was observed during this study that some crewmembers would remove the headset or shift it away from one ear at times to communicate. This may explain the finding that approximately 50% of the subjects reported having difficulty communicating in noise (see Table 11).

Table 12. *Manufacturer specified attenuation for the Racal Slimgard II headset.*

FREQUENCY (HZ)	ATTENUATION, PASSIVE (DB)	ATTENUATION, ANR (DB)
63	9	16
125	12	22
250	20	29
500	25	28
1000	25	25
2000	30	30
4000	37	37

Much of the effort on noise measurements performed by DRDC has focussed on aircraft or naval fleet. The only land vehicle noise that is available in the DRDC Toronto Noise Simulation Facility Noise Library is the Leopard Tank, which was recorded outside the vehicle during a drive-by. The addition of the noise recordings that were made in this study to the Noise Library will increase the range of experiments that can be performed in the Noise Simulation Facility. The information about the noise levels and spectra will help in the selection of appropriate hearing protection for the crewmembers.

Table 13. *Approximate noise exposure with and without the Racal Slimgard II headset.*

VEHICLE	POSITION	CONDITION	UNOCCLUDED	PASSIVE HEADSET	ANR HEADSET
LAV III	Driver	Idling	84	60	57
		Rough terrain	91	70	64
		Highway	97	78	70
LAV III	Crew Commander	Idling	73	52	47
		Rough terrain	91	70	65
		Highway	97	77	70
Bison	Driver	Idling	89	66	64
		Rough terrain	102	78	75
		Highway	102	79	75
Bison	Crew Commander	Idling	89	69	63
		Rough Terrain	102	79	75
		Highway	102	81	75
ADATS	Driver	Idling	95	71	68
		8 km/h	95	72	68
		32 km/h	103	81	78
		32 km/h, hatches closed	115	94	88
ADATS	Operator	Idling	97	73	70
		8 km/h	101	79	74
		32 km/h	113	91	85
		32 km/h, hatches closed	112	91	84

Whole-body vibration exposure

The whole-body vibration measurement results are much more difficult to assess than the noise exposure, because there are no dose-response relationships for the effects of vibration on health or performance. The guidelines for the evaluation of vibration exposure defined by ISO, BSI and the EU provide conflicting "caution zones," "action values" and "exposure limits" meaning that the assessment of a given vibration exposure can be very different depending on which standard is used. In addition, it has been argued that "it is currently not logical to assume that injury will be prevented by any particular exposure action value or exposure limit value" (Griffin, 2004). In this study, an attempt was made to evaluate the vibration exposure according to all three of the standards. This corresponds to 1) a health guidance caution zone bounded by 8.5 and 17 $m/s^{1.75}$ for ISO 2631, 2) an action value of 15 $m/s^{1.75}$ for BS 6841, and 3) action values of 0.5 m/s^2 or 9.1 $m/s^{1.75}$, and daily exposure limits of 1.15 m/s^2 or 21 $m/s^{1.75}$ for the EU directive. It is assumed here that these values are for an 8-hr daily period of exposure, although this is only stated explicitly in the EU directive.

The RMS acceleration values for the LAV III given in Table 7 show that the vibration for the driver, crew commander and passenger exceeded the EU action value of 0.5 m/s^2 for rough terrain, and also the passenger for highway driving. This is consistent with Table 10, which shows that the VDV action value of 9.1 $m/s^{1.75}$ would be reached within 8 hours. The same vibration conditions would fall into, but not exceed, the ISO health guidance caution zone. None of the conditions exceeded the BSI action value or EU daily limit.

The RMS acceleration values for the Bison listed in Table 8 show that the driver and crew commander vibration exposure exceeded the EU limit when driving over rough terrain. The exposure for these two conditions also exceeded the ISO health guidance caution zone and BSI action value, but did not exceed the EU daily limit for VDV (Table 10).

Table 9 shows that the RMS acceleration values for the ADATS exceeded the EU action value for the driver and operator at both of the driving speeds. The EU daily exposure limit was also exceeded in the case of the driver when driving at 32 km/h. In terms of VDV, the EU action value was exceeded for all of these conditions, but not the daily limit. The mobile conditions also fell into the ISO health guidance caution zone, except for the driver at 32 km/h in which the zone was exceeded. The exposure for the operator exceeded the BSI action value for both driving speeds, while the driver exposure exceeded the action value for the higher speed only.

The VDV calculated in this study are estimated (Equation 4), calculated using the RMS accelerations for each 30 sec of vibration exposure. The values are thus conservative and may not reflect the impact of repeated shocks, particularly for the rough terrain condition. Nonetheless, the results give reason for concern regarding the health of armoured vehicle personnel. Many of the conditions that were measured had a vibration exposure that fell into the ISO health guidance caution zone and exceeded the EU action value, and a few conditions exceeded the ISO zone (Bison driver and passenger for rough terrain, ADATS driver for 32 km/h) or the BS action value (Bison driver and passenger for rough terrain, ADATS driver and operator for 32 km/h, operator for 8 km/h).

The vibration spectra for the LAV III generally showed that the vibration in the x- and y-axes was strongest in the 1 to 2.5 Hz range, and the 4 to 5 Hz range for the z-axis. The Bison vibration spectra showed a strong bias towards 1 Hz for all axes except the crew commander z-axis. For the ADATS, the driver x-axis and operator y-axis vibration showed peaks in the 16, 63 and 80 Hz bands (these axes are the same direction, as the operator sits sideways relative to the driver), and the driver y-axis and operator x-axis vibration was strongest around 2 Hz (and 80 Hz for the operator x-axis). The z-axis vibration was more varied across the frequency spectrum, but showed a peak at 80 Hz for the driver for the 32 km/h driving speed, and a peak at 20 Hz for the operator for the 8 km/h speed. There is a lack of concrete evidence linking certain frequencies of vibration to bodily injury or performance degradation. This is especially true for vibration in the x- and y-axes. However, it has been suggested that vibration in the z-axis below 2 Hz are less disruptive than higher frequencies because they do not induce the various body resonances (Griffin, 1990). It has also been suggested that the greatest magnitude of vibration is transmitted to the spine at frequencies between 4.5 to 5.5 Hz and 9.4 to 13.1 Hz (Griffin, 1990).

In general, the noise levels increased with vehicle speed. In the case of the ADATS, which is a tracked vehicle, the vibration also increased with vehicle speed. For the LAV III and Bison, the vibration for two different terrains was considered rather than vehicle speed; however, the vibration levels for highway driving were relatively low compared to the ADATS.

There is little vibration data available for armoured vehicles for comparison to the results of this study. A DCIEM study in 1972 measured M113, M109 Howitzer, M1131/2 Lynx, Centurion tank, M548 Cargo Carrier on snow-packed roads (Maret and Winship, 1972). The vibration was measured by mounting two linear accelerometers on a seat pack, and rotating them through 90 degrees to obtain data for the third axis. The vibration signals were recorded onto a Nagra tape recorder. Much of the data was lost due to equipment failures, and the remaining data could not be compared to that of the current study, as the vehicles are not the same. Forshaw and Ries obtained vibration data for the driver of the M113, 5/4 ton truck and Centurion tank (Forshaw and Ries, 1985). However, the measurement results were given according to the times to reach the old ISO exposure limits that are no longer valid, and the details of the measurement procedure were not provided. The current study used improved electronics equipment that enabled spectral analysis, calculated the results in terms of RMS acceleration and eVDV and evaluated exposure according to the three current standards. It is expected that the results will form a basis for comparison for future measurements and provide guidance on the conditions and exposures that should be used for future experiments.

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Future work

One of the subjects complained about the vibration transmitted to his hands and arms from the steering wheel of the vehicle. This finding suggests that it may be important to include the measurement of hand-arm vibration (HAV) in future studies. In addition, the driver and operators of the vehicles experience addition vibration from the seat-back. Thus, seat-back vibration measurements should be included in the measurement and calculations of the overall vibration exposure. A difficulty is that although ISO 2631-1 encourages seat-back measurements and defines a separate weighting curve, it does not state how the measurements should be included in the assessment of the total vibration exposure.

A recent addition to ISO 2631 gives guidelines for the evaluation of vibration containing multiple shocks (ISO 2631-5; Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 5: Method for evaluation of vibration containing multiple shocks [ISO, 2004]). The new standard was the result of a six-year, five-phase research program performed by the U.S. Army Aeromedical Research Laboratory between July 1991 and July 1997 (Cameron et al, 1998). The standard includes methods and equations for calculating acceleration dose, D_n (where n refers to the x, y or z axis) and an equivalent static compression stress, S_e, resulting from the relationship between the shock exposure and spinal response (ISO, 2004). Interpretation of these values requires more experience with the application of the standard (Alem, 2005) and, likely, knowledge of the biomechanics of the spine. Future health hazard assessment studies in armoured vehicles should consider the use of this standard.

Conclusions

The noise levels in all of the vehicles measured exceeded safe values for unprotected listening (MOL, 1991). Across the vehicles studied, the most intense levels were observed in the ADATS, particularly for the driver when driving with the hatches closed. Communications headsets, in particular the Racal Slimgard II, may provide enough noise attenuation to reduce the noise to safe levels, given that the headset is properly fitted, worn at all times inside the vehicle, and is used in the ANR mode during very noisy driving conditions (i.e. with the hatches closed, driving at high speeds). The use of earplugs in combination with the headset is another possiblity, provided that the earplug does not interfere with radio communications. The data showed that noise levels were lowest in the LAV III, which is the newest of the vehicles measured. The noise recordings made in the vehicles assessed will provide an important addition to the DRDC Toronto Noise Library, which had previously been lacking in armoured vehicles recordings. These will be used in study hearing, communication and cogitive function in the Noise Simulation Facility.

The vibration levels and dose values for LAV III, Bison and M113A2 ADATS were evaluated according to the ISO, BSI and EU standards. While the vibration exposure did not exceed the EU exposure limits for an 8-hr day for any of the vehicles, many of the conditions produced vibration levels that should be regarded as potentially harmful. The vibration exposure depended on the type of terrain and the vehicle speed, which are factors that likely cannot be controlled in practice. It is recommended that seatbelts be worn when available, and that the time spent inside the vehicle while mobile is limited, using the data in Table 10 as a guideline. This study also provided information about the vibration spectra for three vehicles, which was not previously available. This data may be useful in the design of future studies on the effects of vibration on performance.

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List of Acronyms/Abbreviations

ADATS	Air Defence Anti-Tank System
ANR	Active Noise Reduction
APC	Armoured Personnel Carrier
BSI	British Standards Institute
CF	Canadian Forces
CFB Borden	Canadian Forces Base Borden
CFSEME	Canadian Forces School of Electrical and Mechanical Engineering
CSA	Canadian Standards Association
DAVPM	Directorate of Armoured Vehicle Project Manager
dB	Unit for unweighted Sound Pressure Level
dBA	Unit for A-weighted Sound Pressure Level
ISO	International Organization for Standardization
LAV	Light Armoured Vehicle
MOL	Ministry of Labour
SPL	Sound Pressure Level

Appendix A: Armoured Vehicle Photos

Figure A1. M113A2 front view

Figure A2. M113A2 cabin

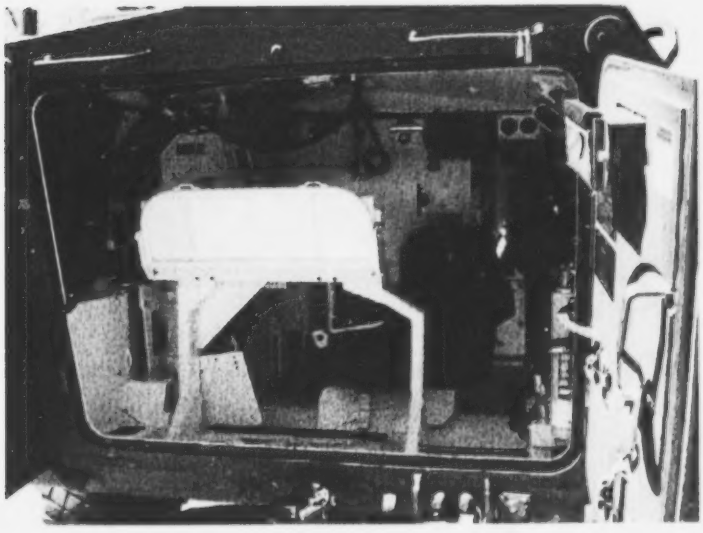

Figure A3. Coyote navigator seat

Figure A4. LAV III

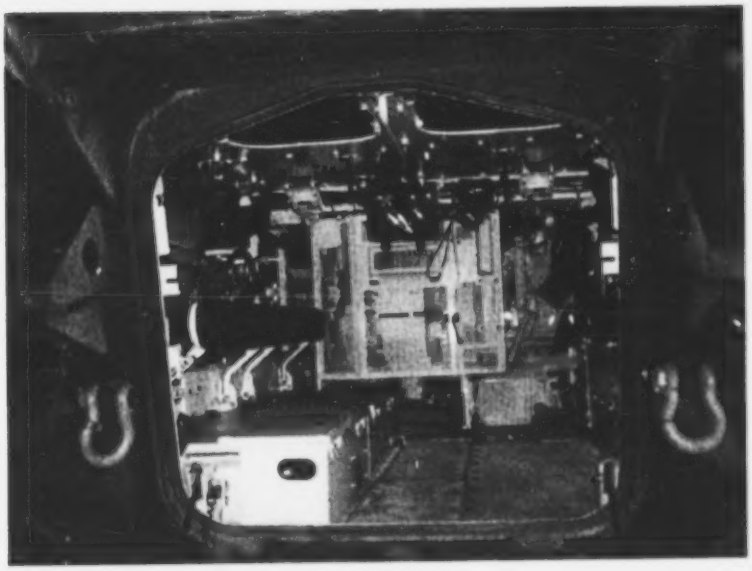

Figure A5. LAV III cabin

Figure A6. Bison MRT variant

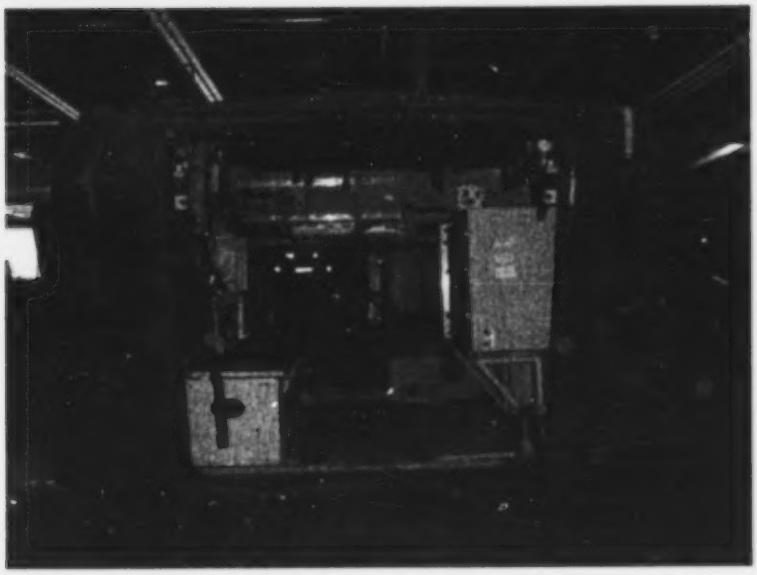

Figure A7. Bison MRT variant cabin

Figure A8. M113 ADATS

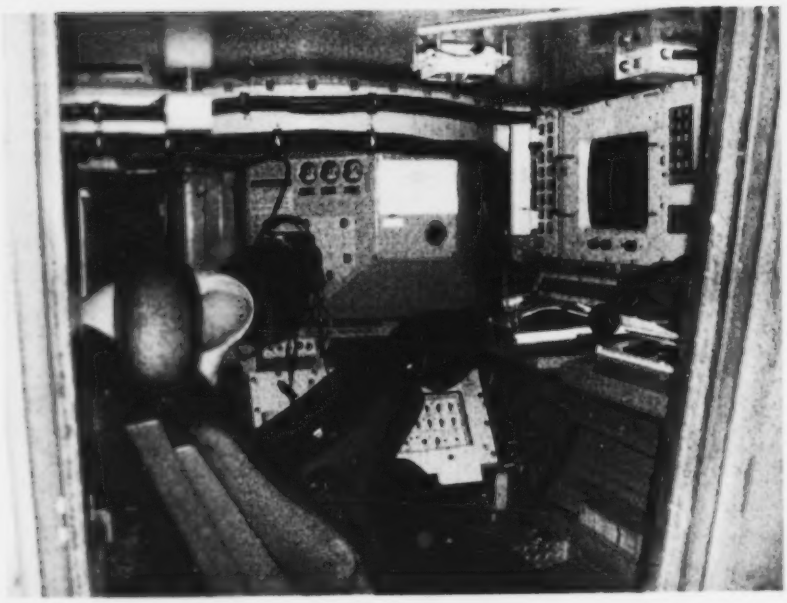

Figure A9. M113 ADATS operator seats

Appendix B: Noise data

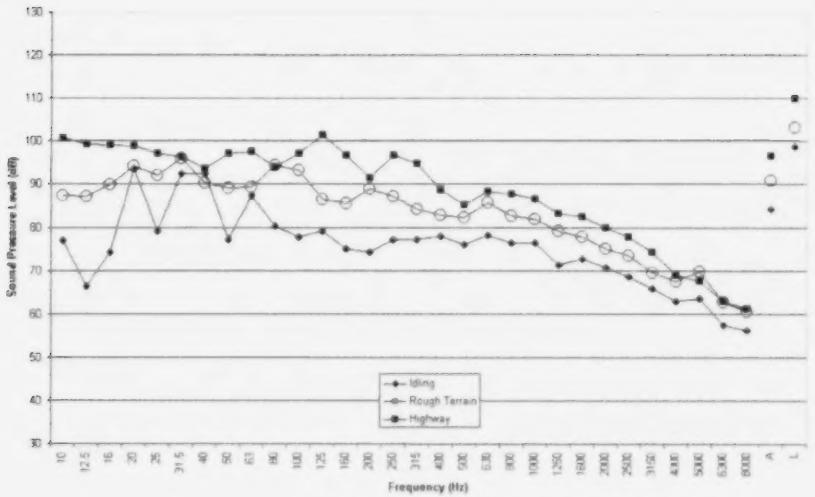

Figure B1. LAV III driver noise

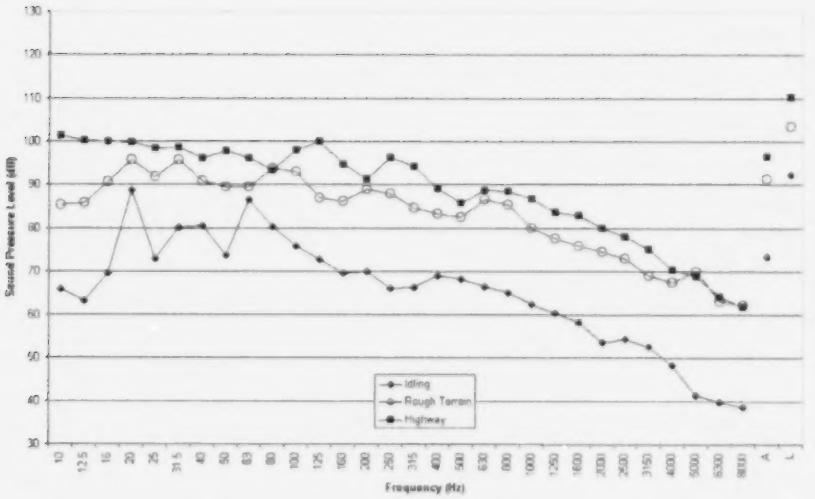

Figure B2. LAV III crew commander noise

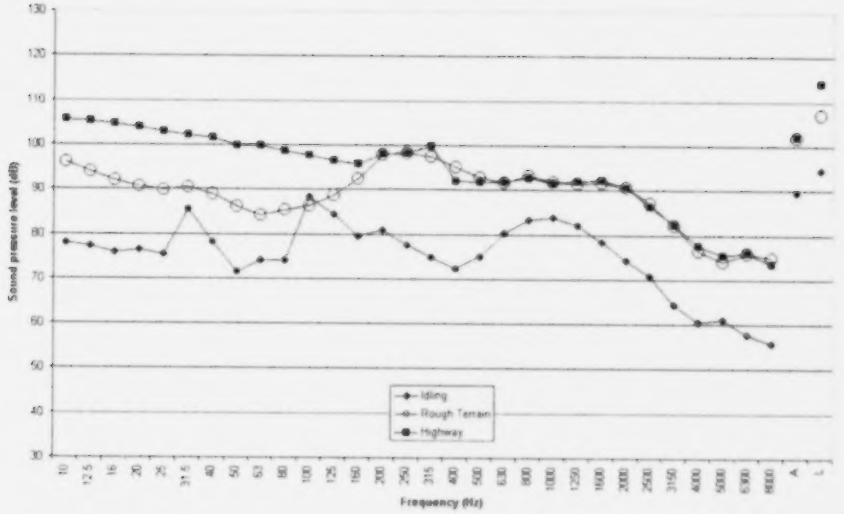

Figure B3. Bison driver noise

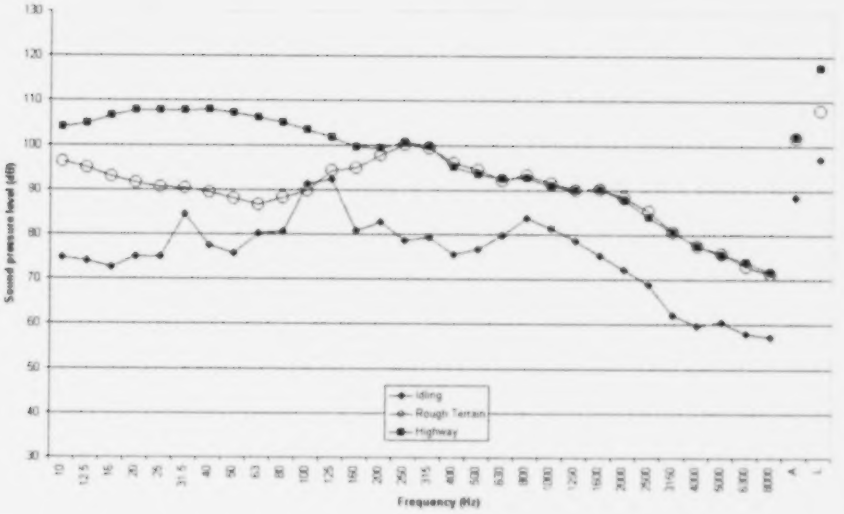

Figure B4. Bison crew commander noise

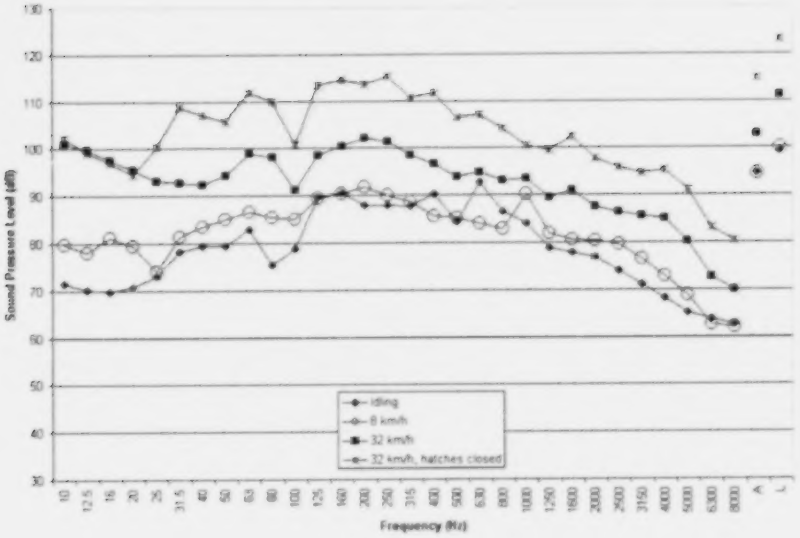

Figure B5. M113 ADATS driver noise

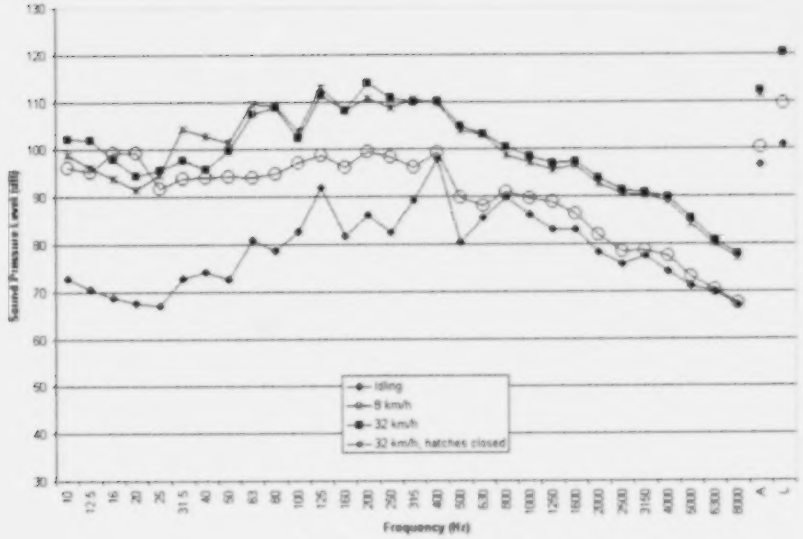

Figure B6. M113 ADATS operator noise

Appendix C: Whole-body vibration data

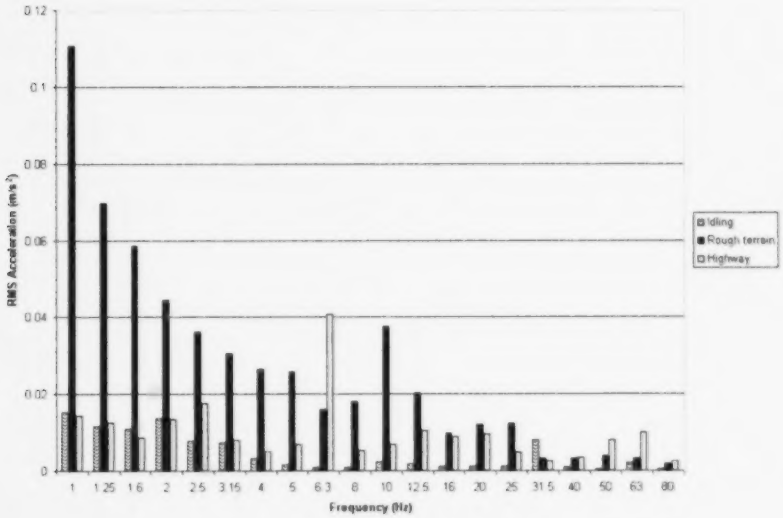

Figure C1. LAV III driver x vibration

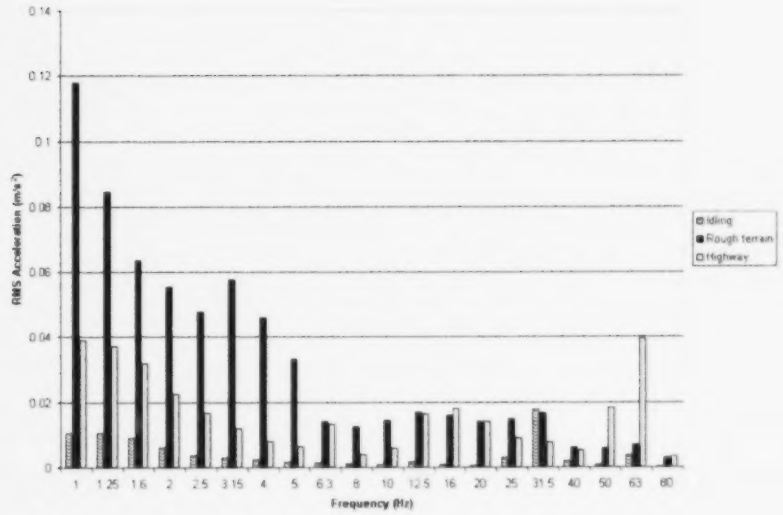

Figure C2. LAV III driver y vibration

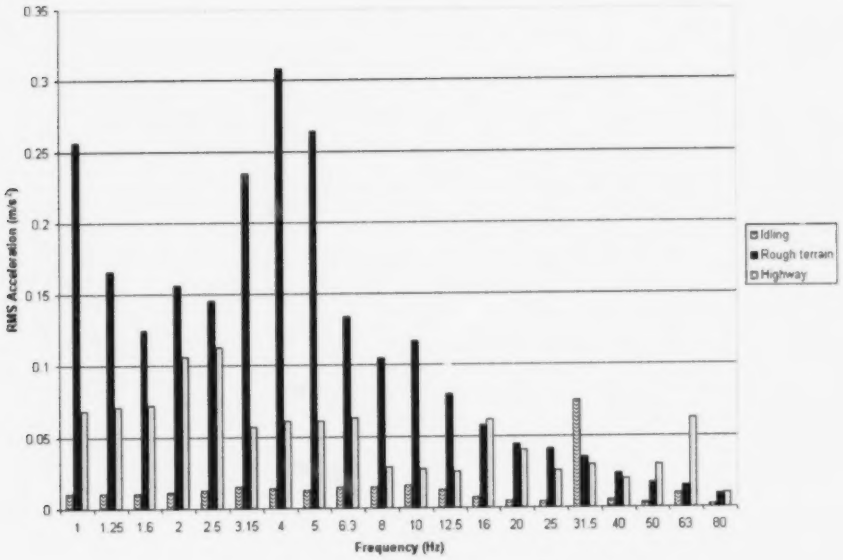

Figure C3. LAV III driver z vibration

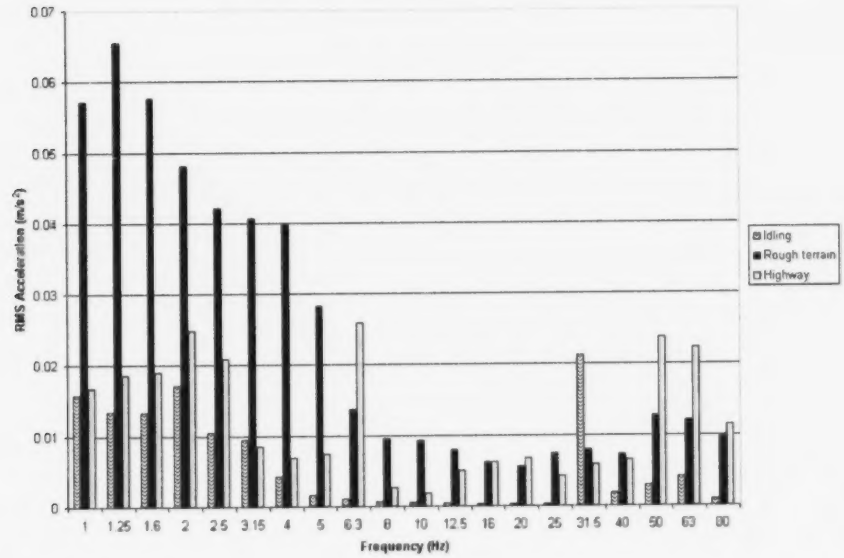

Figure C4. LAV III crew commander x vibration

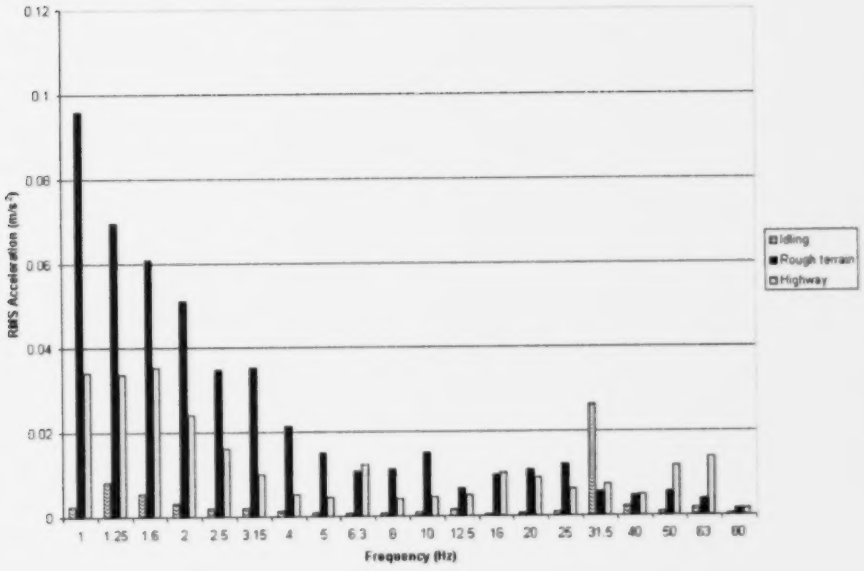

Figure C5. LAV III crew commander y vibration

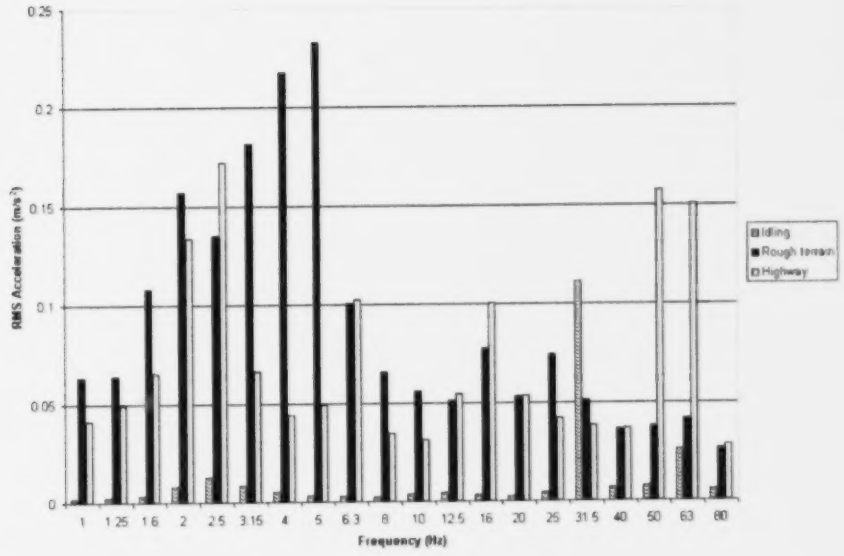

Figure C6. LAV III crew commander z vibration

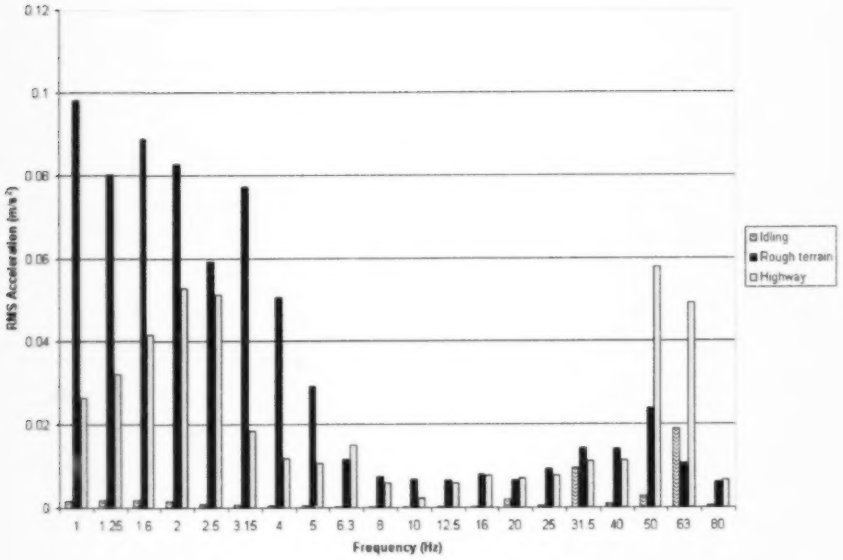

Figure C7. LAV III passenger x vibration

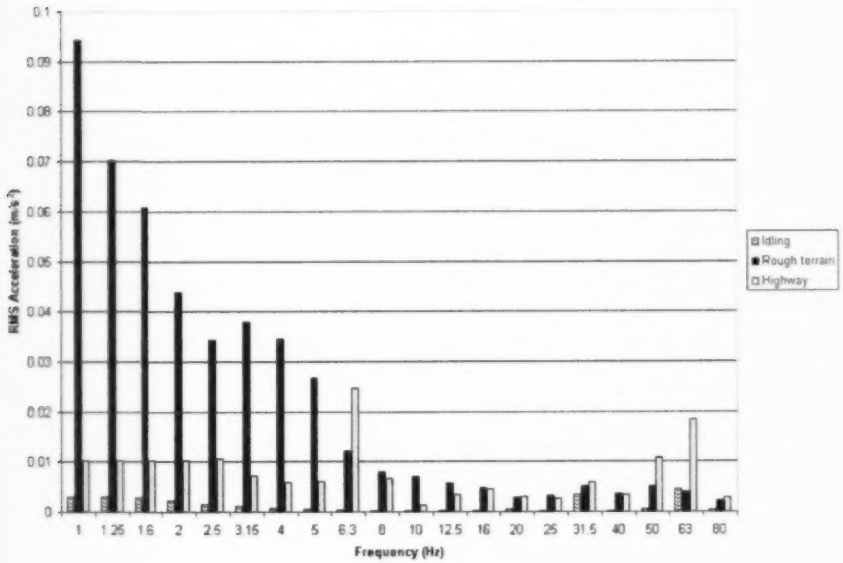

Figure C8. LAV III passenger y vibration

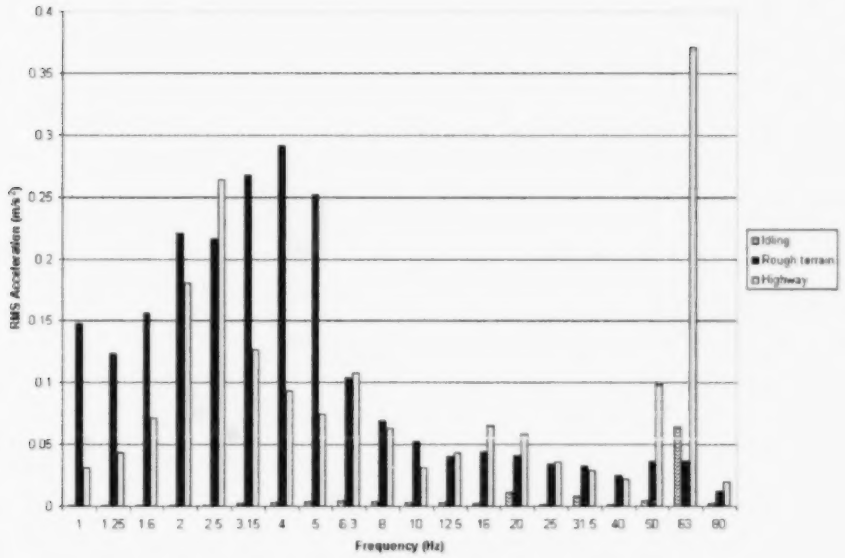

Figure C9. LAV III passenger z vibration

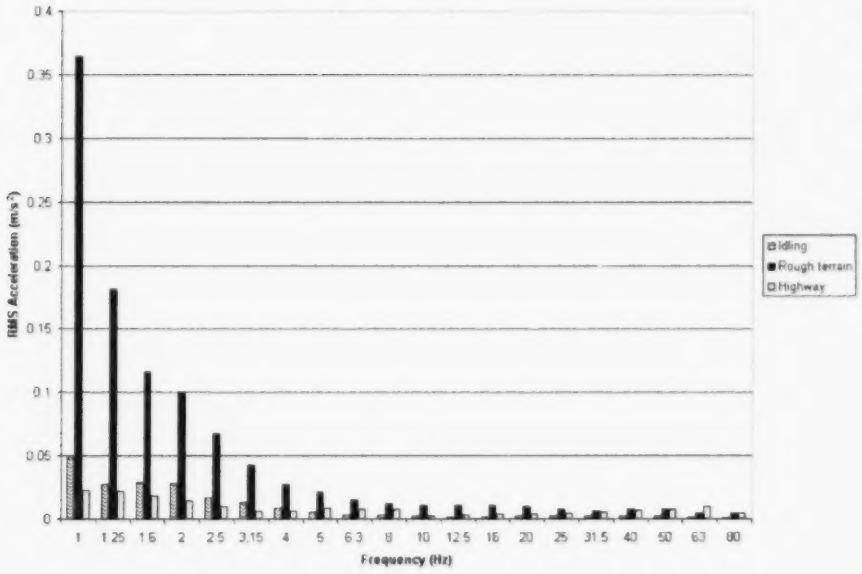

Figure C10. Bison driver x vibration

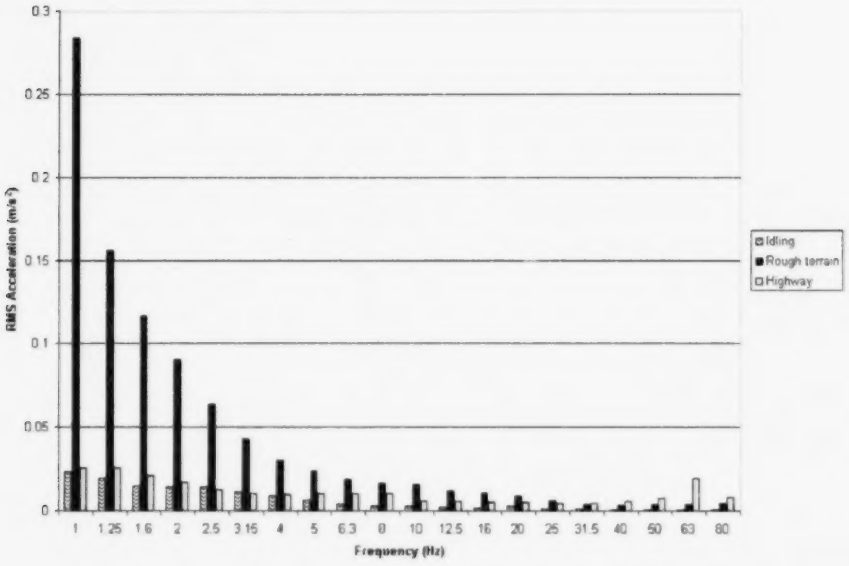

Figure C11. Bison driver y vibration

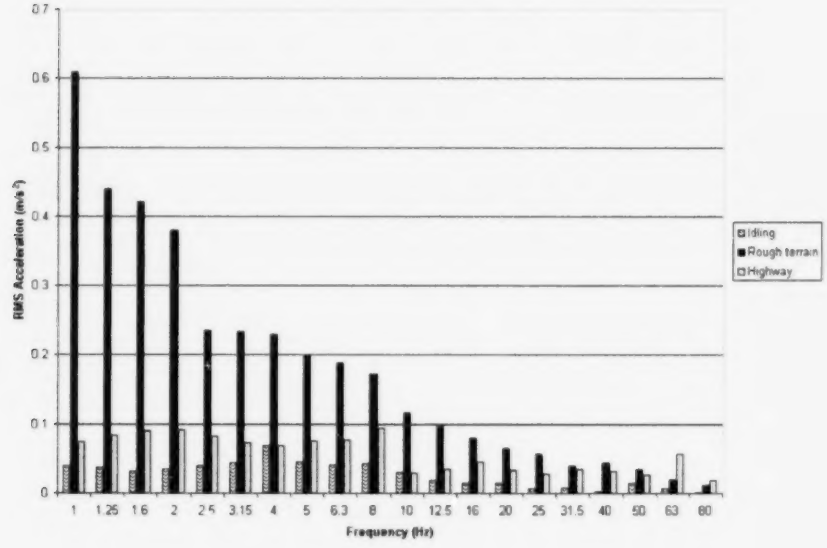

Figure C12. Bison driver z vibration

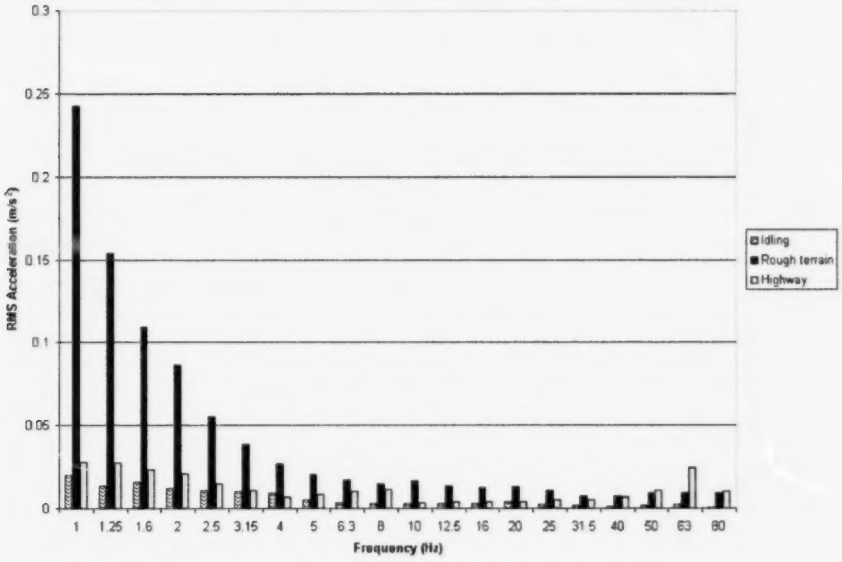

Figure C13. Bison crew commander x vibration

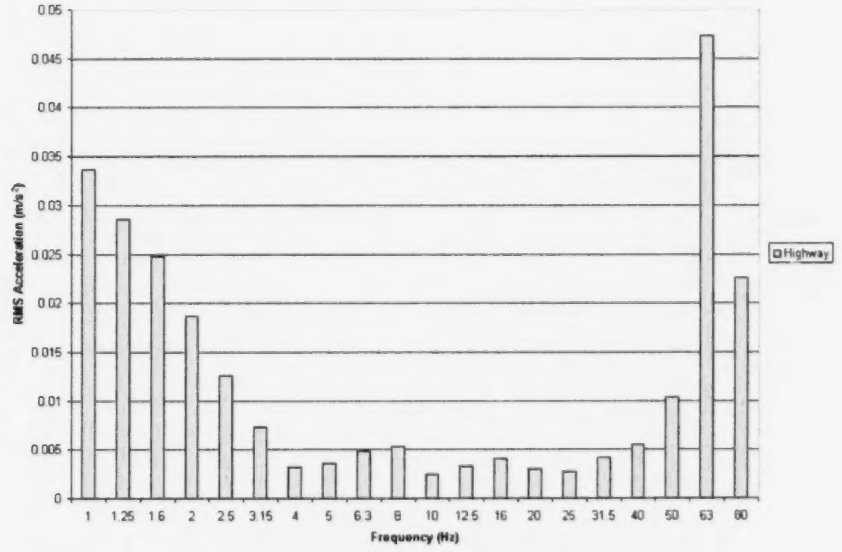

Figure C14. Bison crew commander y vibration

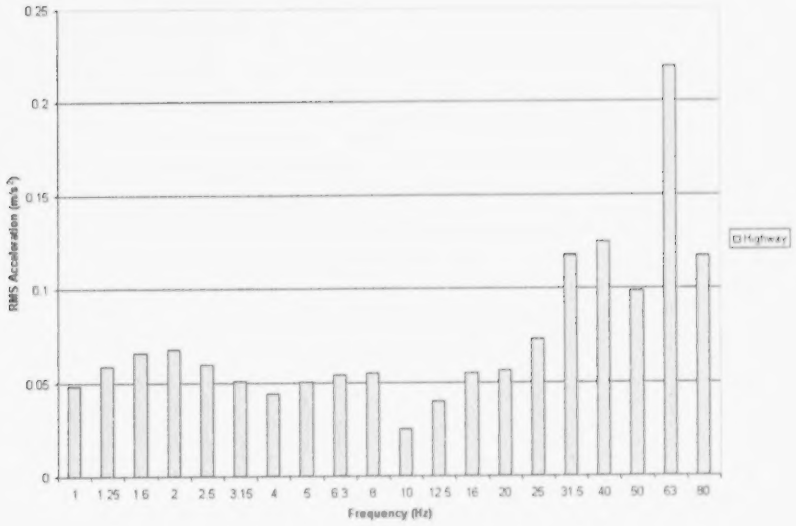

Figure C15. Bison crew commander z vibration

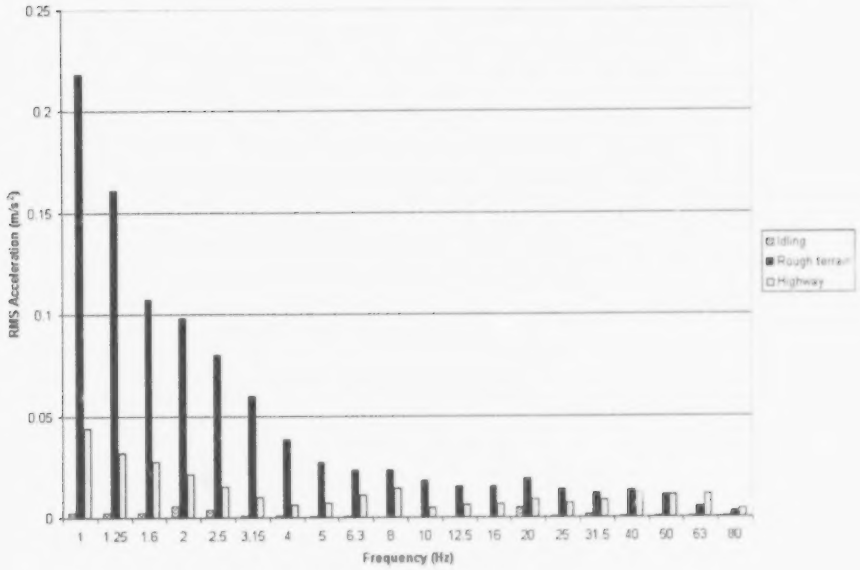

Figure C16. Bison passenger x vibration

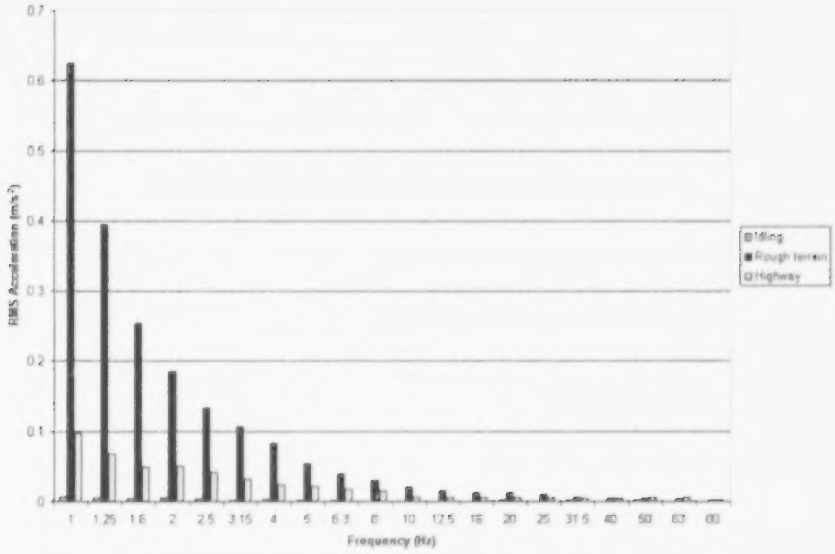

Figure C17. Bison passenger y vibration

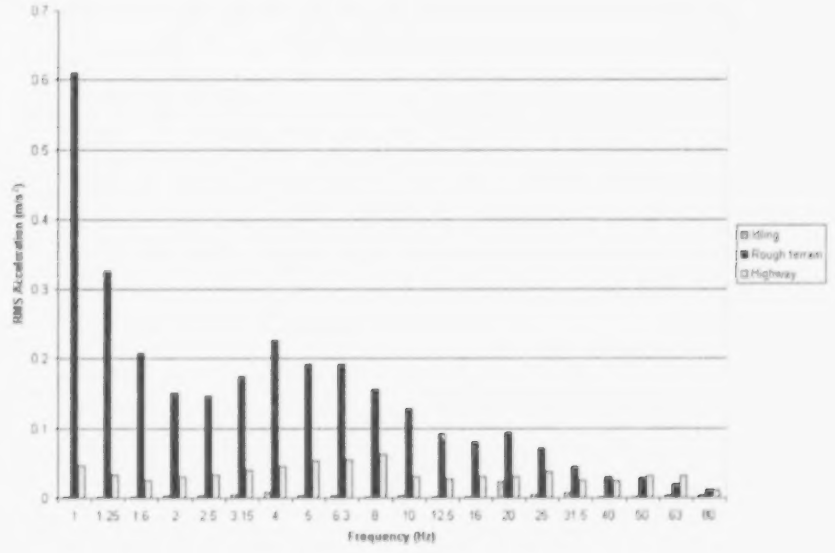

Figure C18. Bison passenger z vibration

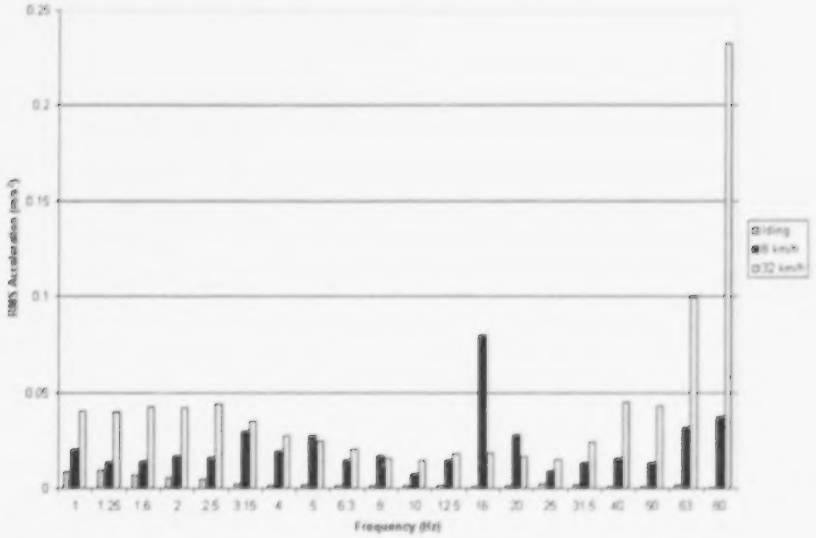

Figure C19. M113 ADATS driver x vibration

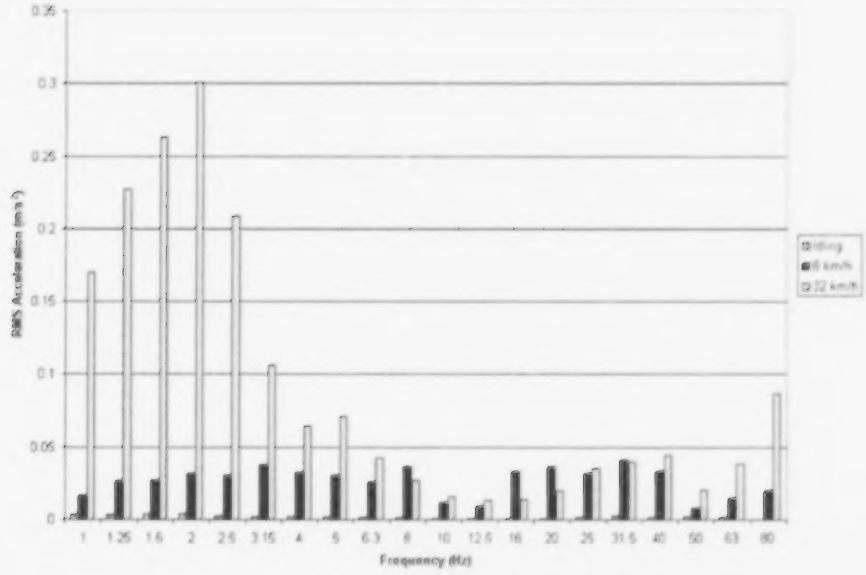

Figure C20. M113 ADATS driver y vibration

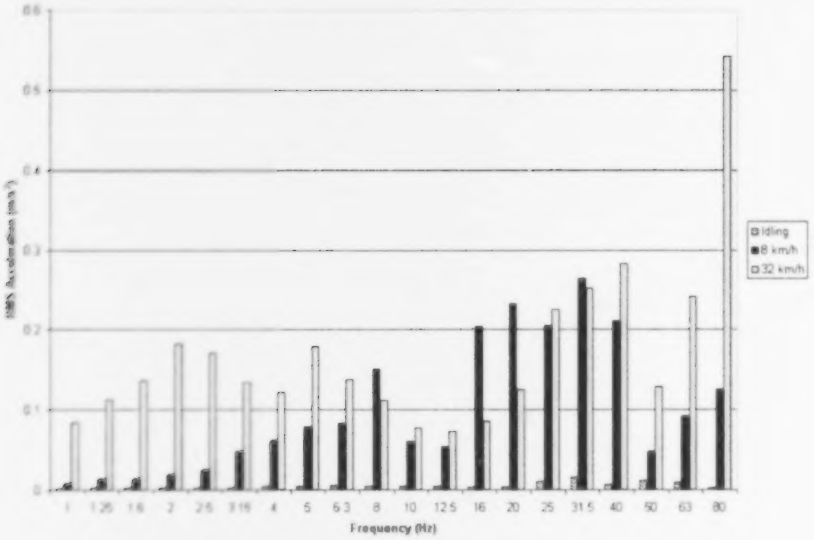

Figure C21. M113 ADATS driver z vibration

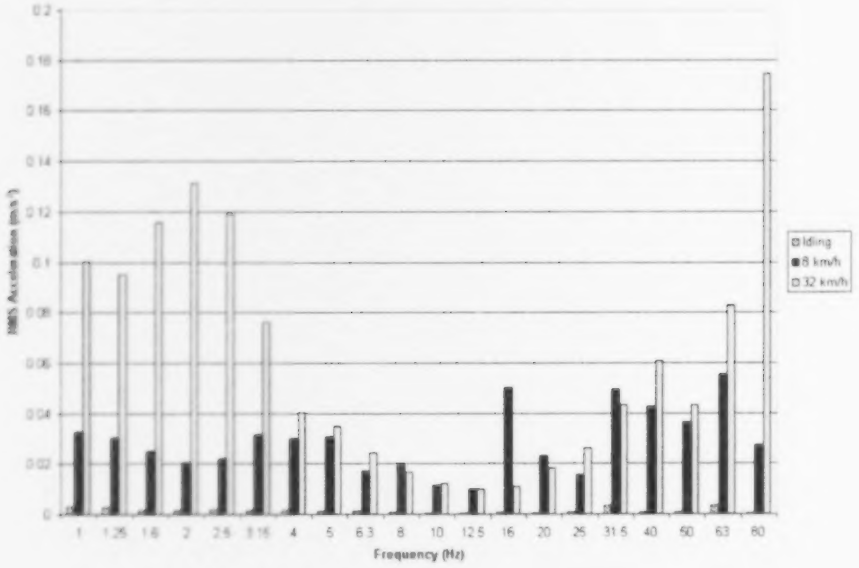

Figure C22. M113 ADATS operator x vibration

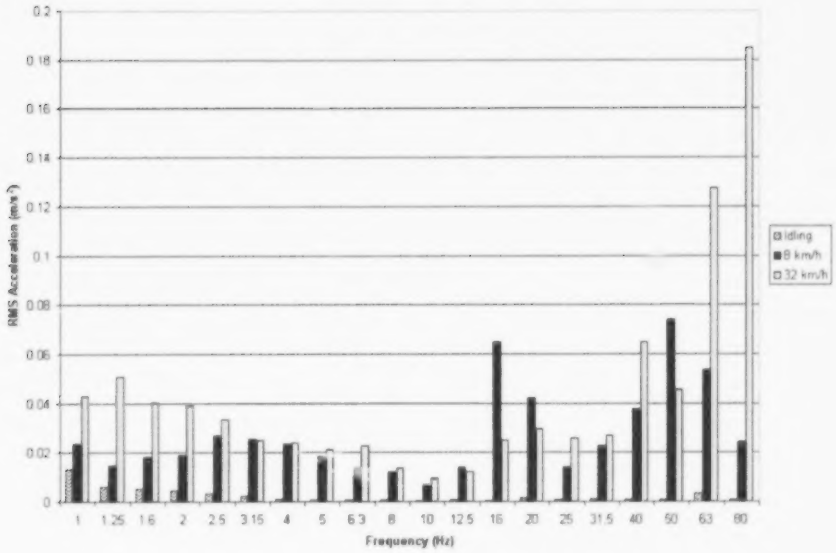

Figure C23. M113 ADATS operator y vibration

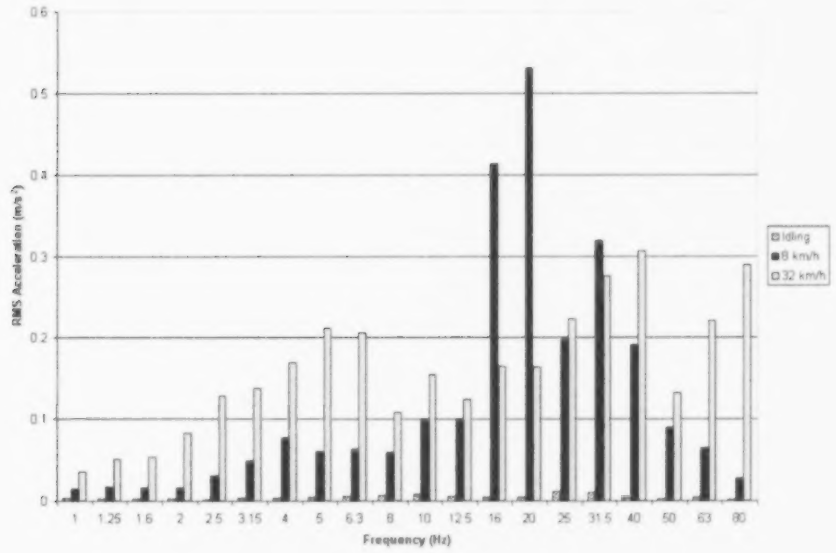

Figure C24. M113 ADATS operator z vibration

Appendix D: Questionnaire

DRDC Toronto Protocol #L-492

CHARACTERIZATION OF VIBRATION AND NOISE EXPOSURE IN CANADIAN FORCES LAND VEHICLES

Reaction to vibration and noise questionnaire

Subject number: _____

1. Date: _____

2. Name: _____ 3. Service ID: _____

Subject number: _____

4. Age: _____ 5. Gender: _____

6. Weight (kg): _____ 7. Height (cm): _____

8. Vehicle used: _____

9. Position (driver, crew commander, passenger): _____

10. Dosimeter Serial No. _____

11. Microphone placement: _____

12. Headgear worn: _____

_____

Please respond to the following questions by circling 1 = not at all, 2 = not really, 3 = neutral, 4 = somewhat, 5 = very much.

13. When inside the vehicle (on-road/high speed), the vibration made me uncomfortable.	1	2	3	4	5
14. When inside the vehicle (off-road/slow speed, the vibration made me uncomfortable.	1	2	3	4	5
15. When inside the vehicle (on-road/high speed), the noise made me uncomfortable.	1	2	3	4	5
16. When inside the vehicle (off-road/slow speed), the noise made me uncomfortable.	1	2	3	4	5
17. When inside the vehicle (on-road/high speed), the noise made it difficult to communicate.	1	2	3	4	5
18. When inside the vehicle (off-road/slow speed), the noise made it difficult to communicate.	1	2	3	4	5
19. When inside the vehicle (on-road/high speed), I experienced circling of myself and /or surroundings	1	2	3	4	5
20. When inside the vehicle (off-road/slow speed), experienced circling of myself and /or surroundings	1	2	3	4	5
21. When inside the vehicle (on-road/high speed), I felt nauseous (felt like vomiting).	1	2	3	4	5

22. When inside the vehicle (off-road/slow speed), I felt nauseous (felt like vomiting).	1	2	3	4	5
23. When inside the vehicle (on-road/high speed), I felt pain. If so, where? _____	1	2	3	4	5
24. When inside the vehicle (off-road/slow speed), I felt pain. If so, where? _____	1	2	3	4	5
25. After leaving the vehicle, I experienced circling of myself and/or surroundings.	1	2	3	4	5
26. After leaving the vehicle, it was difficult to find my footing (lack of balance).	1	2	3	4	5
27. After leaving the vehicle, I felt nauseous (felt like vomiting).	1	2	3	4	5
28. After leaving the vehicle, I felt fatigued.	1	2	3	4	5
29. After leaving the vehicle, I felt pain.	1	2	3	4	5

If so, where? _____

THANK YOU VERY MUCH FOR PARTICIPATING IN THIS SURVEY. THE INFORMATION THAT YOU PROVIDE WILL BE KEPT CONFIDENTIAL. RECORDS WILL NOT IDENTIFY YOU PERSONALLY.

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Caractérisation de l'exposition au bruit et aux vibrations dans les véhicules terrestres des Forces canadiennes

4. AUTHORS (First name, middle initial and last name. If military, show rank, e.g. Maj. John E. Doe.)

Ann M. Nakashima, Matthew J. Borland, Sharon, M. Abel

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(U) Measurements of whole-body vibration and noise were made in several Canadian Forces (CF) armoured vehicles to quantify and assess the exposure levels according to national and international standards. The measurements were made in the M113A2, Coyote, LAV III, Bison and M113A2 ADATS (air defence anti-tank system). In all vehicles except the ADATS, noise and vibration signals were recorded when the vehicles were idling, driven over rough terrain and driven on the highway. The ADATS was assessed while idling, driven at 8 km/h and driven at 32 km/h on a paved track. For each condition in each vehicle, the vibration and noise were recorded at the crewmember positions inside the vehicle for 5 to 10 minutes. The measurements were made at the driver, crew commander and passenger positions in the M113A2 and Bison, the driver, crew commander and operator positions in the Coyote, and the driver and operator positions in the ADATS. The crewmembers were also asked to complete a Reaction to Noise and Vibration questionnaire at the completion of each vehicle measurement session. The ADATS was the noisiest of the vehicles measured, while the LAV III was the least noisy. Although the noise levels in all of the vehicles while mobile exceeded the Canadian Labour code exposure limit of 87 dBA for 8 hours (MOL, 1991), it was found that in most cases the noise exposure could be reduced to safe levels with the proper use of an effective communications headset. The vibration exposure was more difficult to assess because of the conflicting caution zones, action levels and exposure limits set by the various standards. However, the results indicated that caution should be taken with respect to the duration of vibration exposure. The questionnaire responses indicated that half the crewmembers had difficulty communicating in the vehicle noise, but few were affected by vibration. The latter result may be due to the relatively short exposure duration (there was no indication of a negative response to the vibration exposure).

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(U) noise, noise exposure, mechanical vibration, whole-body vibration, armoured vehicles